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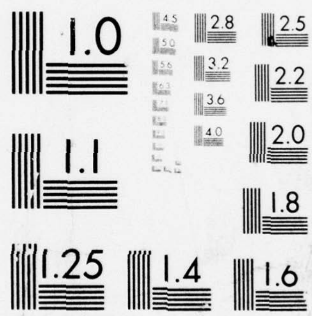

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by

10 WILLIAM ROBERT YOUNG

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in partial fulfillment of the requirement for the degree of

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ABSTRACT

Freezing Precipitation in the

Southeastern United States. (May 1978)

William Robert Young, B.S., Colorado State University

Chairman of Advisory Committee: Prof. Walter K. Henry

An investigation of various surface and upper-air parameters and their relationship to the occurrence of ice storms in the southeastern United States was conducted to determine as many relationships and ranges of values as possible. Four storms in the past 10 years were selected and studied in detail. Temperature, dew point, wind, visibility, and pressure were the surface parameters considered, while 850-mb temperature, 850-mb dew point, 700-mb temperature, 850-mb wind, 850-mb/700-mb averaged wind direction, and 1000-500 mb thickness were the upper-air parameters considered. Various combinations of parameters also were considered. Data consisted primarily of 215 soundings of winter weather types in or around ice storms from 1968-1977 for the months of December through early February.

Results involved a decision checklist that utilizes surface temperature, surface dew point, 850-mb temperature, 1000-500 mb thickness, temperature/dew point spread and 850-mb/700-mb averaged wind direction. It was found that if the criteria in the decision checklist are met, then a most probable forecast of precipitation type can be obtained by using the derived decision graph involving surface temperature and 850-mb temperature.

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I. INTRODUCTION

A. Definitions, descriptions, and dimensions

Perhaps more than any other type of winter storm, the ice storm can paralyze the area it covers both in terms of traffic and of communications. It may inflict appreciable monetary damage. An example of freezing precipitation coating trees is shown in Fig. 1, a photograph taken during a storm in College Station, Texas, on 6 November 1959. It is most commonly referred to as an ice storm, a glaze storm, or freezing rain (or freezing drizzle). According to Ludlum (1971), another name by which it is known is a "silver thaw." But by any name, the millions of dollars in damage it does to valuable timber alone is reason enough to justify further study (Metcalfe, 1949). The fact that it occurs in relatively narrow bands (a band 185 km wide is an extreme case, 55-110 km is more likely) makes it very difficult to forecast. Thus it becomes a major headache not only for the populace directly affected but also for the local forecaster. A temperature difference of a few degrees can cause an area to change from moderate rain to freezing rain or snow!

Willett and Sanders' (1959) definition for glaze (freezing precipitation) is "the condition which is produced by the freezing of supercooled raindrops when they strike cold objects on the ground." When these drops are large enough to "splash" when hitting

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The citations on these pages follow the style of the Journal of Applied Meteorology.

Fig. 1. Freezing precipitation in College Station, Texas on 6 Nov. 1959.

an object, they will form on that object a coating of slick and more or less transparent ice. Longley (1970) says, "...at times, rain falls from a warm layer aloft through a layer of air below freezing. The raindrops become supercooled and turn to ice on collision with solid objects such as aircraft, trees, wires, or ground. This is freezing rain. If the rain freezes before reaching the earth, it becomes frozen rain or sleet." Bryson and Hare (1974) state that as, "It [freezing rain] falls from warm overriding air in deep cyclones in which a shallow wedge of subfreezing air is trapped near the ground." Finally, Geiger (1950) says, "Glaze is probably the most sensitive symptom of changing ground conditions. It is recognized that glaze forms in two ways, either through the solidification of supercooled precipitation on the warm ground or through the freezing of rain drops (above 0°C) on the very cold ground." In regards to duration (of a glaze coating), Ludlum (1971) says, "... a study of recent winter seasons showed that an ice coating seldom endures for more than seven days."

Many other authors, among them Humphreys (1942), Byers (1959), Battan (1962), and Petterssen (1969), could be quoted, but the principle remains virtually the same. No matter where it occurs, the basic conditions are: a shallow layer of sub-freezing air near the ground with warmer, moist air overriding it (provided the air is sufficiently moist to produce steady rainfall). The ideal location for such a storm would be ahead of a warm front which is moving over a cold (below freezing) surface. Thus a sounding indicating freezing precipitation at the surface should always be marked by a shallow

wedge of cold air and a sharp rise in temperature aloft to a peak temperature, warmer than freezing, generally at some level between 850 and 700 mb.

B. Freezing precipitation - a worldwide problem

Since a surface temperature of at least freezing is needed in order to produce freezing precipitation, there are obvious limitations to the areas of the globe where freezing precipitation can occur (note: some cases occur with an air temperature slightly above freezing but these are in locations where the ground has been cooled below freezing and remained so, although the air temperature had climbed above 0°C). However, it is still a much more extensive problem than generally is realized.

Ice storms often occur in Europe, particularly in Germany. They also occur in the United Kingdom as reported by Pedgley (1969), who discussed a very intense storm affecting those islands in December 1968. England experienced an even more severe ice storm in January 1940. Ice storms also strike (rather heavily at times) in parts of USSR, mainland China, and Japan. Such storms even occur in areas of the world one would never associate with freezing precipitation. Wylie (1958) gives one such example in a report on ice storms during February 1957 in Hawaii!

Montreal, Canada, is one large city quite frequently hit by damaging ice storms. Mahaffy (1961) and Chainé (1973) documented two such storms in February 1961 and March 1972, respectively, each of which resulted in total damages running into the millions of dollars. Other large cities (within the United States) which are frequently

affected are, for example, Boston, Buffalo, New York, Philadelphia, Cleveland, Springfield (Ill.), Omaha, St. Louis, Kansas City, Topeka, Dallas/Ft. Worth, Amarillo, Austin, Memphis, Nashville, Little Rock, Atlanta, and Portland (Oregon).

In the continental United States, ice storms affect almost all of the individual states, but according to Kiviat (1949) the area of greatest frequency of ice-storm occurrence is "... a crescent-shaped arc extending from Central Texas northeastward to Missouri and Illinois then eastward across the Ohio Valley and the lower lakes to New England and the middle Atlantic states." This is the area of maximum conflict between the warm, moist Gulf air and the cold polar or arctic air masses. Particularly heavy storms occurred in the midwest in February 1883, December 1924, and January 1959 (Joos, 1959). Areas of minimum occurrence of ice storms would be the Southwest, where it is generally too dry, and Florida, where it is usually too warm. A map of ice storm frequency within the continental United States (Kimble, 1955) is presented in Fig. 2. Note that this survey was done in 1934 and it is felt that a more recent survey would show higher frequency of occurrence especially in the Southeast.

There have been many damaging ice storms across the United States in the past 25-30 years. Information on the extent of the damages produced by these storms is documented in the Local Climatological Data assembled by the National Oceanic and Atmospheric Administration (NOAA) and printed by the National Climatic Center (NCC) in Asheville, North Carolina. Much of the information in this

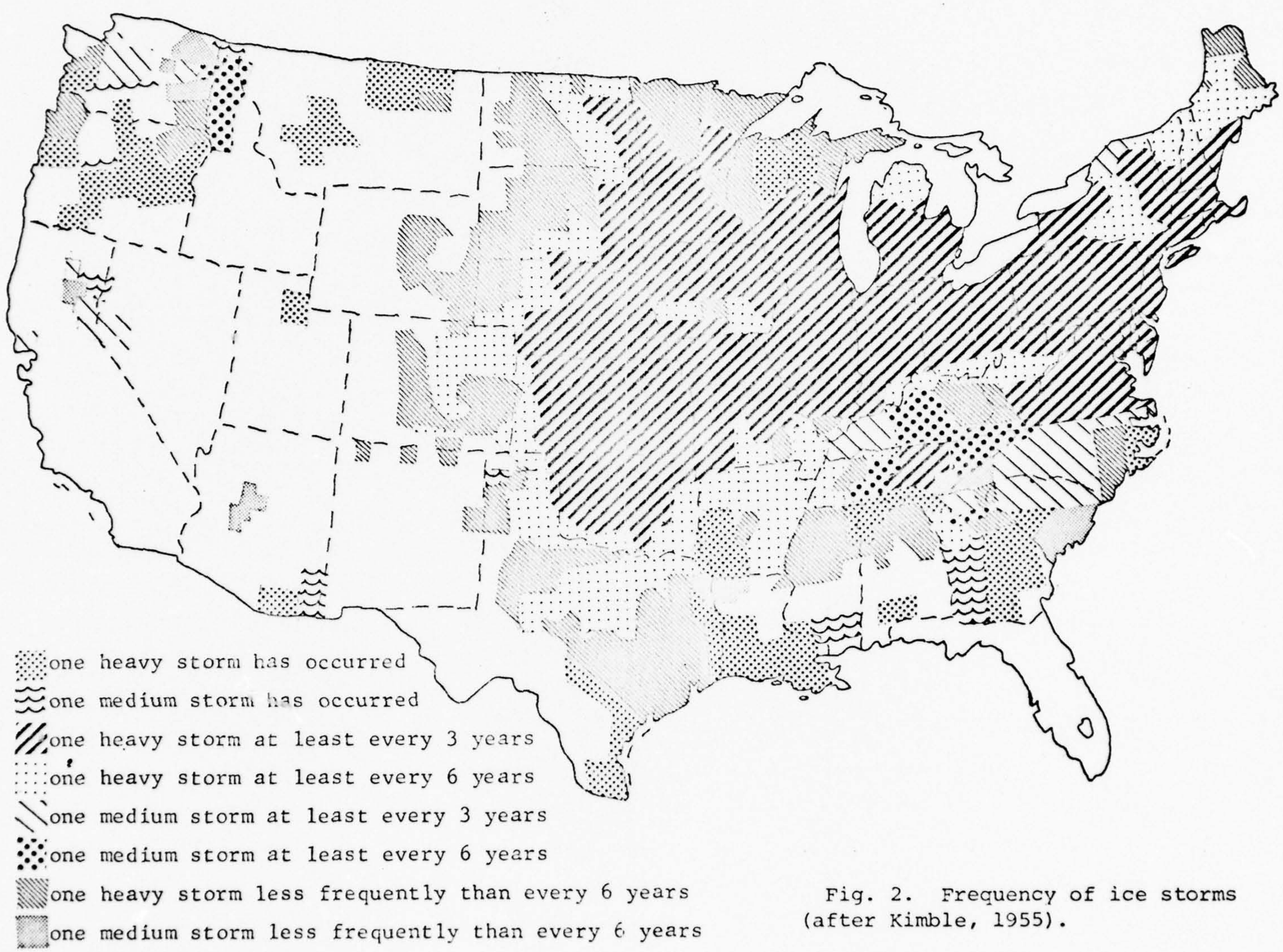

Fig. 2. Frequency of ice storms (after Kimble, 1955).

paper in regards to storm damage comes from these publications. Some notable storms since 1951 are listed in Table 1.

Two facts are clear from this table--ice storms occur most everywhere in the United States, and where they do, they cause great damage. A fine reference for further discussion of damaging ice storms during the past 100 years is the Weather Record Book compiled by Ludlum (1971).

C. Freezing precipitation as a problem in the southeastern United States

The area selected for this study consists of Georgia, Alabama, Mississippi, Louisiana, Tennessee, Arkansas, and the eastern one-third of Texas (Fig. 3). Most ice storms in this area occur between late December and early February, a time span which combines the period of coldest temperatures with the period of most frequent cyclogenesis in the Gulf of Mexico (Saucier, 1949). There is a plentiful source of warm, moist air available from the nearby Gulf of Mexico (particularly during those periods of cyclogenesis along frontal boundaries which are in the Gulf). Generally all that is needed is for a wedge of cold air to penetrate far enough into the area (and yet not too far) so as to cool temperatures near the surface into an appropriate range. With so much moisture available, when a mass of cold air does push into this area and the right conditions of overrunning do exist to produce an ice storm, the tendency is for the storm to be even more intense than the average storm farther to the north or west. This, coupled with the fact that

Table 1. Some ice storms in the continental United States over the past 30 years.

Date	Place	Damage	Ice Accumulation	Remarks
Jan 1951	Most of Southeast	$100 million	-----	See text (chapter 1)
Mar 1960	northern Alabama	$20 million	-----	See text (chapter 1)
Dec 1967	SW Minnesota	Over $500,000	-----	Knocked out power 3-4 days
Jan 1968	SE Oklahoma	-----	.9 - 1.3 cm	One of worst traffic jams in state's history
	Arkansas	$1.5 million	-----	6 killed, storm did damage in 90-140 km band. See text (chapter 3)
	North and Central Louisiana	over $500,000	up to 2.54 cm	See text (chapter 3)
	South Carolina	$500,000	-----	-----
Feb 1969	North and South Carolina	Over $50 million	-----	some areas, power out up to 2 weeks
Dec 1969	Southern half of Maine	Over $500,000	-----	worst storm in many years in area
Jan 1970	Oregon	over $5.5 million (to orchards and utilities)	up to 4 cm	caused by rainfall from overriding warm air falling through stagnant cold air in Columbia

Table 1. (Continued)

Date	Place	Damage	Ice Accumulation	Remarks
				River Basin. One of worst in this area since Nov. 1921 (see Kiviat, 1949)
Feb 1970	N. half Kentucky	-----	-----	mixed with snow. Worst this area since 1951
Dec 1970	Iowa	over $500,000	-----	12 auto deaths
Jan 1971	N. half Md.	over $50,000	-----	over 300 traffic injuries
	N. half Ohio	over $50,000	-----	more than 850 auto accidents; 3 killed
Dec 1972	Texas	over $500,000	-----	Dallas/Ft Worth; Austin hardest hit
	N. 1/3 Miss.	over $5 million	-----	-----
Jan 1973	Most of Southeast	over $200 million	-----	See text (chapters 1 and 3)
	Texas	over $50 million	-----	
	Atlanta	over $25 million	10.4 cm	
Feb 1973	S. half of La, Miss,Ala	over $1.5 million	-----	See text (chapter 3)

Table 1. (Continued)

Date	Place	Damage	Ice Accumulation	Remarks
	N. and S. Carolina	over $3 million	-----	most damage to poultry industry
Jan 1974	S. Ark	over $5 million	-----	Thousands of homes without power
	W, Cntrl, NE KY	over $500,000	-----	3 killed; 75 injured
	NW 1/2 Miss	over $5 million	-----	-----
	W. Tenn.	$4.5 million	over 5 cm on ground	16 traffic deaths
Dec 1975	Central and West N. Carolina	over $100,000	-----	worst in area in 30 years; 4 killed, 11 injured
Jan 1977 (2-3)	N. Tex, Ark, La, Miss, Ala and Ga.	over $6 million	2.5 - 7.75 cm	3 killed in Ala; 1 killed in La.
Jan 1977 (22-24)	Ark, S. Mo., Ky, Tenn, La, N. Ala, N. Ga.	-----	-----	See text (chapter 3)

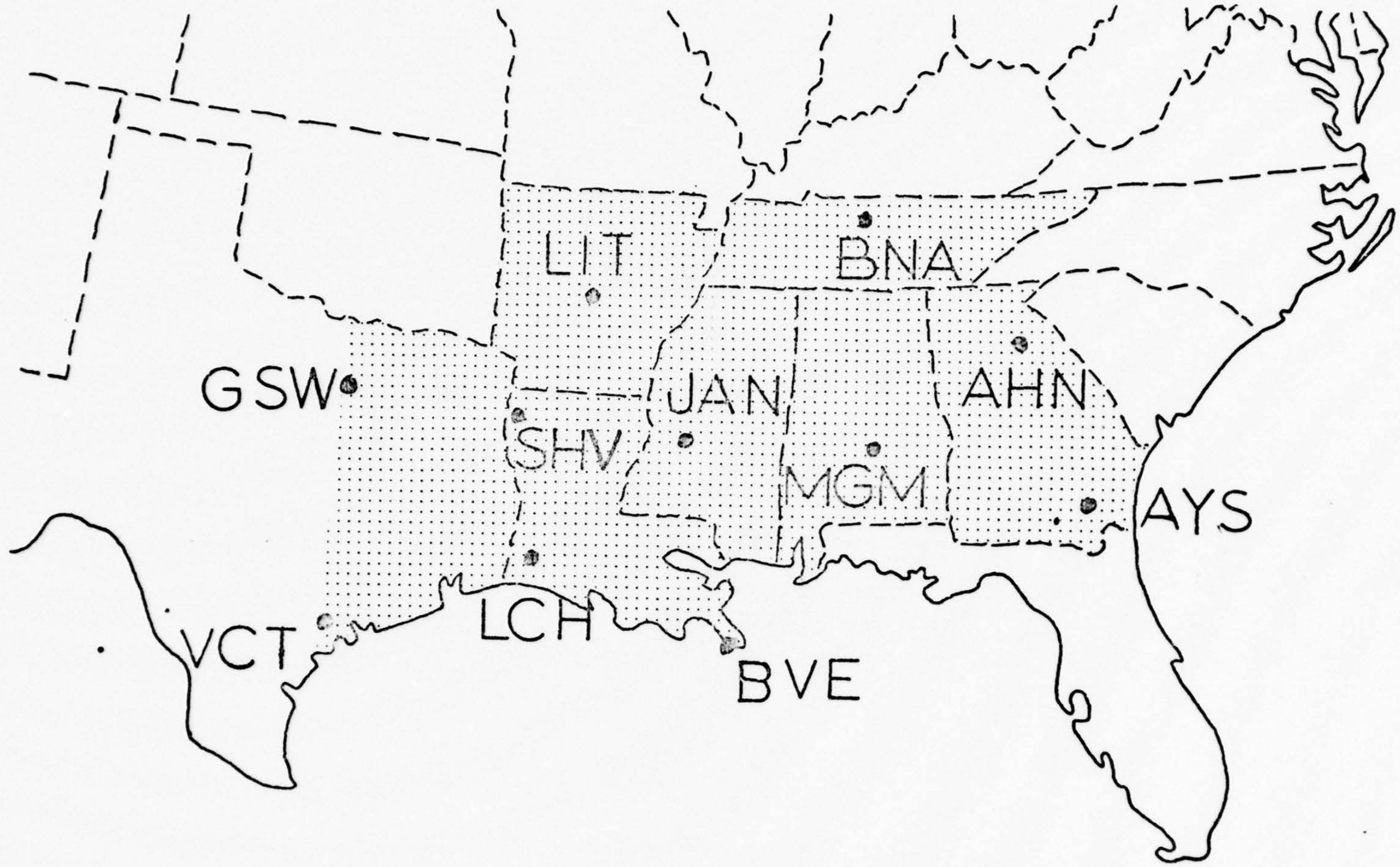

Fig. 3. Area of study. Stations indicated are radiosonde stations within area.

generally the South is less adept at handling winter storms (due to their relative infrequency), results in this area having the most damaging and costly ice storms on record.

The great southern glaze storm of January 1951 (Harlin, 1952; Ludlum, 1971) was one of the most destructive ice storms on record. It caused $100 million in damages (in 1951 dollars!) in a 185-km swath from Louisiana and northern Alabama to West Virginia. Also, very heavily affected was northeastern Texas. Another ice storm, although limited to a much smaller area (northern Alabama), in March 1960 caused $20 million damage (Williams, 1960). The most costly ice storm of all occurred on 7-8 January 1973 and most heavily affected Alabama, northern Georgia, and South Carolina with total damages running near $200 million. For Georgia, it was the worst storm of this type since 1935 and probably the most destructive (monetarily) in history (Ludlum, 1974). Damage in the Atlanta area alone, where 10.4 cm of freezing rain fell, was well over $25 million. The city was paralyzed for two days and had communications hampered for a week. Some schools were closed for a week or more. In Alabama it was the worst ice storm since the aforementioned 1960 storm, with nearly a million dollars in damages to trees alone. These and other significant storms occurring in the southeastern United States (in the past 30 years) are listed in Table 1.

The amount of ice forming on exposed objects varies from storm to storm. According to Ludlum (1971), this coating usually ranges from very thin to about 2.5 cm thick but "deposits up to 8" in diameter were reported in north Idaho on 1-3 Jan. 1961, up to 6" in

NW Texas on 22-24 Nov. 1940, and 6" also in New York State on 29-30 Dec. 1942."

Damage done by an ice storm depends largely upon the total amount of precipitation which falls. Glaze is clear ice with a density of near 0.9 gm/cm^3 (Bryson and Hare, 1974) that collects on telephone poles, wires, trees, roofs, and anything else on which it lands that is cold enough to freeze the already supercooled moisture. Telephone poles, wires, and trees can support an unbelievably great weight before they snap, but the rapid accumulation of ice from freezing rain produces just such a great weight. Ludlum (1971) states that, "It has been estimated that an evergreen tree 50 ft high with an average width of 20 ft may be coated with as much as five tons of ice." Kimble (1955) said of the ice storm in England at the end of January 1940, "... it was found that 11 tons of ice was being supported by some of the telegraph poles before they finally snapped; individual wires carried as much as 1,000 pounds of ice." An article by Carr (1949) also discusses the problem of ice accumulation on telephone poles.

To give a better idea of how localized this phenomenon really is, Harms (1974) states that "... in northern latitudes, the freezing rain band accompanying a major snow storm is usually on the order of 25 to 30 n mi in width whereas in the southern states the band can be 50 n mi or more in width." Translating these values into metric units, Harm's values become 45 to 55 km for a northern latitude storm and 92.5 km or more for a southern storm. As stated previously, in the 1951 storm, the band was 185 km in width, while in the January

1973 storm, the band was about 110 km wide. It should be emphasized that these two storms were exceptionally strong and thus do not represent most storms.

D. Objectives

For all the discomfort caused by ice storms, both in a physical and an economic sense, very few detailed studies have been made on them as a separate entity. Also, most previous studies were made using one or two parameters only and in the rare cases three, with the effects of other parameters neglected. Thus a study needs to be done to examine as many of the parameters and facets of freezing precipitation as are practical and useful while treating freezing precipitation as the main theme, not just as a sideline to a study on snow vs rainfall. Relationships such as the depth of the cold air and warm air and their relative temperatures will aid the forecaster in prediction of these storms and thus will present a more complete picture of the phenomenon.

This study began with two main goals. The first goal was to study four individual storms within a limited geographical area (in this case, the southeastern United States) and to trace their development in relation to a range of parameters, both surface and upper-air. The second objective involved tabulating the data obtained from the four storms and arriving at as detailed a prediction tool as was possible. As will be seen in chapter two, the data sample was expanded to include soundings from all of the eastern United States and additional dates in order to achieve a representa-

tive data sampling.

E. Recent studies

Most available studies on forecasting ice storms relate to the surface temperature and/or the 850-mb temperature or the 850-mb dew point (or some other level within the warmer air, say 700 mb). Others involve the use of wet-bulb temperatures (to allow for moisture), both surface and 850-mb, the dew-point depression, various computed thicknesses, and combinations of the above parameters.

Brenton (1973) listed some 53 references mainly concerning snow forecasting but many of which also delineated between frozen and liquid precipitation types. The most applicable studies are referenced in this paper but the reader is referred to Brenton's work because of its completeness.

Williams (1960) and Kimble (1955) point out one further factor which must be considered, viz., station elevation. Kimble gives an example of a storm in January 1953 during which one New Jersey village received up to 3.81 cm of freezing precipitation while a neighboring village, only 45 m lower in elevation, received none. Williams, in discussing the 1960 ice storm in northern Alabama, points out that while many valley stations were unaffected, stations 245 to 300 m higher in elevation experienced very heavy icing. Also, the difference in elevation helps to account for the occurrence of ice storms in Hawaii (Wylie, 1958), where they are found generally above 2700 m in elevation.

Bryson and Hare (1974) found surface and ground temperatures usually to be in the range of 0°C to -5°C, and although their study was for Canada, that range holds true for most other places. They found that if temperatures in the wedge of cold air dropped lower, the precipitation fell as sleet or ice pellets. In the major ice storms previously mentioned, the swath of heaviest ice deposit was where surface temperatures were within this range in almost every case. Even the storms in England and Hawaii follow this pattern, and thus it can be accepted as a prerequisite for freezing rain (as opposed to freezing drizzle, which can occur at much colder air temperatures).

Booth (1970) used dew point and dew-point depression as indicators. He states that snow <u>never</u> occurred with a surface dew point equal to or greater than 3°C and rain <u>never</u> occurred with a surface dew point equal to or less than -3°C. He further suggested a relationship between dew point (DP) and dew-point depression (DPD) to define the boundary between snow and precipitation other than snow: if DPD $\leq$ [(-2 DP) + 1]°C, then the chance of snow exceeds 50 per cent provided that the dew point is less than or equal to 0°C. This method could be used further to divide the rain and snow sectors with the freezing precipitation generally falling along or near the dividing line.

In regard to forecasting in Georgia, Harms (1974) states that, "... in general, snow will occur north of the 850-mb 0°C isotherm, and freezing rain and sleet in a 30 to 60 n.m. band to the south." This conflicts somewhat with the rule-of-thumb expounded by Diercks

(1970) in which he stated that, for the eastern United States, a mixture of snow, sleet, and rain including freezing rain should be predicted with predicted 850-mb temperatures of between 0°C and -2°C (with snow falling where temperatures are colder and rain where they are warmer).

Hilworth and Bailey (1971) used 1000 and 850 mb wet-bulb temperatures* and devised a decision graph for forecasting rain, freezing rain, mixed precipitation types, or snow (Fig. 4). Russell (1970) also described an objective forecast method for winter precipitation that used a decision graph. His technique involved predicted surface and 850-mb temperatures and dew points. He indicated that most cases of freezing precipitation should occur between the location of the surface 0°C isotherm and the 850-mb 0°C isotherm. Also, the wet-bulb temperatures should be used wherever possible to offset the effects of evaporation and condensation (Russell provided graphs to arrive at these parameters). Booth (1973) tested Russell's decision graph by using United Kingdom data and added a few modifications to the graph. His results, although giving a high percentage of correct forecasts, were somewhat inconclusive since most of the cases could have been forecast based on surface temperature alone.

A very recent study on freezing precipitation was accomplished by Bocchieri (1977). He used the parameters of boundary layer potential temperature (BLPT) and 1000-500 mb thickness (both quantities given in terms of their deviation from 50% values) to

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*Their study was for the area east of the Rocky Mountains and so they assumed that the surface was at 1000 mb.

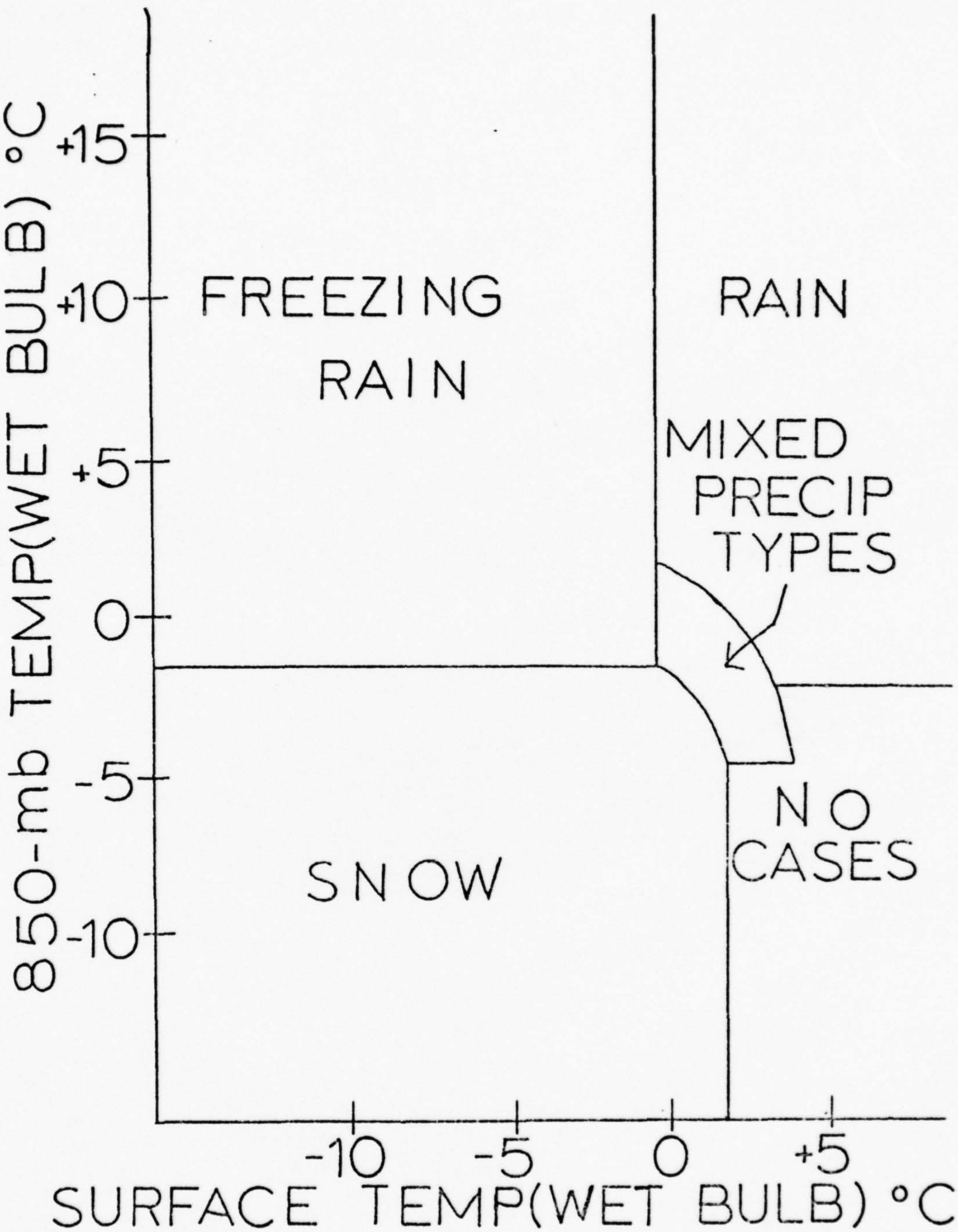

Fig. 4. Decision graph developed by Hilworth and Bailey, 1971. Study was for the area east of the Rocky Mountains with the surface generally assumed to be at 1000-mb.

devise a 12-to-24-h forecast tool (a relative frequencies graph) for occurrence of freezing precipitation. He defined BLPT as "... the mean potential temperature in the boundary layer in the LFM model. The boundary layer in the LFM model is 50 mb thick with the bottom of the layer at the earth's surface." A 50% value is defined as "that value at which the conditional probability of frozen precipitation is 50%." He tried several other pairs of parameters (various thicknesses as well as the 850-mb temperature and BLPT) before finally arriving at the resulting graphical aid.

Wagner (1957) used mean temperature from 1000 to 500 mb as an indicator of precipitation type. He indicated that 1000-700 mb thickness would be an even better prediction parameter but 1000-500 mb thickness was used because of its greater availability. His results indicated that if the thickness value at the station differed from a value called its "equal probability" value by more than 30 m, then the type of precipitation could be specified. This "equal probability" line was the thickness value at the stations for which the occurrence of frozen and unfrozen precipitation forms were equal. His results showed a confidence of 75 percent or more when the thickness at a station is at least 30 m from the equal probability value for that station (in regards to specifying the incidence of frozen and unfrozen precipitation forms).

Several of the above studies were expounded upon further in Tang's (1973) thesis which is concerned mainly with snow prediction and in particular with the snowstorms of January and February 1973. He considered three main parameters, namely, surface temperature,

850-mb temperature and 1000-500 mb thickness. The rule-of-thumb he devised to forecast freezing precipitation was, "If the 850-mb temperature is higher than 0°C, the surface temperature is less than or equal to 0°C, and the 1000-to-500-mb thickness is less than or equal to 5460 m then freezing rain most probably will occur." Tang, however, did concede in an earlier discussion that freezing rain was possible under the same conditions of surface temperature and thickness but with an 850-mb temperature less than or equal to 0°C. A decision graph based on the rules devised by Tang is depicted in Fig. 5.

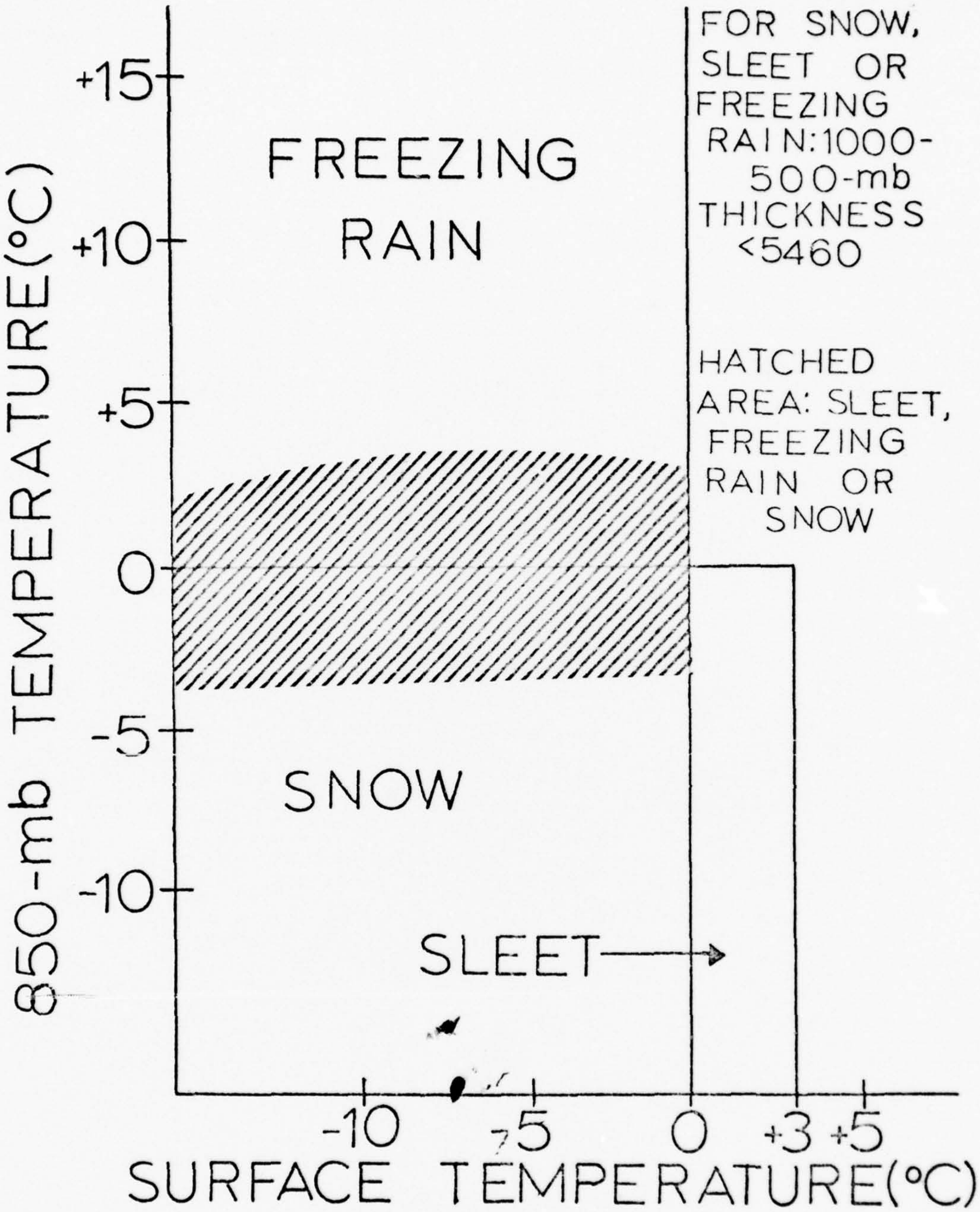

Fig. 5. Decision graph derived from work done by Tang (1974) using 850-mb temperature, surface temperature, and 1000-500 mb thickness.

II. DATA SELECTION

A. Area of study

The area of this study includes eastern Texas (from Dallas/Ft. Worth eastward), Arkansas, Louisiana, Mississippi, Alabama, Tennessee, and Georgia. The area is bounded roughly by 83W to 97W and 37N to 29N (Fig. 3). The states were selected as those most "heavily" influenced by overrunning warm air from the Gulf of Mexico in a winter precipitation situation. Florida was excluded because freezing precipitation is a very rare occurrence in that state. States farther north and west were omitted because different synoptic situations and more prolonged cold spells tend to influence the reporting of weather type to a larger and larger degree (this will be discussed further in a later chapter).

In order to obtain a sufficient sample of soundings reporting freezing precipitation at the surface, soundings were included from most of the United States (mainly the eastern half) with allowances made for station elevation (mountain soundings were avoided). Maximum effort was made to get as many soundings as possible from the study area, but this was restricted by the limited number of radiosonde stations in the area (11), each producing only two soundings every 24 hr (at 0000 and 1200 GMT) and the relative brevity of freezing precipitation occurrence at any one station.

B. Storms

Four storms during the past 10 years were identified as representative storm types. They ranged in intensity from the storm

in February 1973, which produced relatively little freezing precipitation (it later did produce a tremendous amount of snow), to the storm of January 1968, which was of moderate intensity, to the storm of January 1973, which perhaps could be labeled the most severe of its type ever recorded in that area. Specifically, the four storms chosen were:

1. 8-13 January 1968 (actually several storms within that time span)
2. 7-8 January 1973
3. 8-9 February 1973
4. 21-24 January 1977

These storms will be discussed briefly in the following chapters in regard to damage, synoptic situation, and collective surface and upper-air parameters observed. The collective results will be combined with the overall sounding sample base (which includes the soundings from outside the study area) to arrive at the cumulative results.

C. Synoptic Data

The meteorological data used in this study consisted for the most part of radiosonde soundings and surface maps (from Service A and Service C data) and facsimile products of the National Weather Service. Particular charts used were:

1. surface analysis
2. 1000-500 mb thickness analysis
3. 700-mb and 850-mb upper-air analysis

4. radar summaries

5. weather depictions

6. composite moisture index chart

D. Other Data

Additional data consisted of:

1. The Local Climatological Data assembled by the National Oceanic and Atmospheric Administration and published by the National Climatic Center in Asheville, North Carolina. This information provided three valuable aids in producing this study.

a. It provided the detailed information on storm damages discussed in chapters one and three.

b. It helped pinpoint areas of freezing precipitation for the selected storms studied.

c. It indicated periods of freezing precipitation throughout the United States that aided in locating soundings for the overall data sample.

2. AVE soundings

The data for NASA's Atmospheric Variability Experiment (AVE III) was used as an after-the-fact verification for the decision graph and checklist compiled from this study. Material was obtained from NASA TECHNICAL MEMORANDUM X-64938, George C. Marshall Space Flight Center, Alabama, June, 1975. The data consisted of synoptic charts and soundings from 41 rawinsonde stations obtained for 6 February 1975 0000 GMT through 7 February 1975 at 1200 GMT (00, 06, 12, 15, 18, 21 GMT soundings). Data from this time period were not used in the

total sample in order that this could be used as an unbiased check of the results.

III. DESCRIPTION OF SYNOPTIC SITUATION FOR SELECTED STORMS

A. Storm of 8-13 January 1968

1. Effects on area, and background

The southeast United States felt some effects of the storm of 8-13 January 1968 as early as the 2 January when a band of ice spread into Arkansas. This, however, was not the main storm but merely a harbinger of things to come 5-6 d later. The main storm was associated with a frontal boundary which had not moved into the Gulf of Mexico. From 2-13 January, over $1.5 million in damages resulted in Arkansas alone, particularly the east and east-central with six fatalities and numerous injuries. The band of freezing precipitation was 80-120 km wide and persisted tenaciously.

From 8-10 January a major storm produced more than 1 cm of glaze on Oklahoma roads. From there it swept into Arkansas and central Louisiana (over $500,000 in damages), Tennessee, northern Mississippi and Alabama, and finally northern Georgia (over $100,000 in damages). The storm later affected South Carolina (particularly the northern two-thirds with over $500,000 in damages) and eventually created a strong winter snow storm along the eastern seaboard as it progressed into its later stages. All together, it resulted in well over $5 million in damages throughout the area.

2. Development

This storm probably can be described better as a series of storms during the period of 3-13 January 1968. A frontal boundary

in the midwest on 2 January pushed into the Gulf of Mexico by early on the 4th of January, while an intense winter high was building in the northern part of the Canadian province of Manitoba. By 5 January, the front extended from the southern tip of Florida to a wave just off the coast of Texas, while a second frontal boundary stretched from a wave in Wisconsin across southern Nebraska to southern Oregon. At this time, the still-building high had begun to move southeastward towards North Dakota. Some freezing precipitation resulted over the next few days as this front pushed into the Gulf and reinforced the boundary already there. Meanwhile, the cold high had moved into Missouri by 1200 GMT on 7 January and lowered surface temperatures in the Southeast dramatically.

On the 8th of January a strong wave began to develop in the western Gulf, and by the 9th, a deepening low along the front was just off the Louisiana/Texas coast. The cold high had moved in a more easterly direction over the previous 24 h and now formed an east-west ridge from Missouri to Virginia. As a result, a strong overrunning situation was established with a wedge of very cold air trapped near the surface and extensive freezing precipitation affecting Oklahoma and Arkansas most heavily at first, but soon spreading eastward over large portions of the Southeast (see Figs. 6 and 7, showing the synoptic situation and a vertical cross section, respectively).

The low continued to develop and move ENE across southern Alabama but damped out in the Atlantic. Other waves developed along the frontal boundary and produced varying degrees of freezing pre-

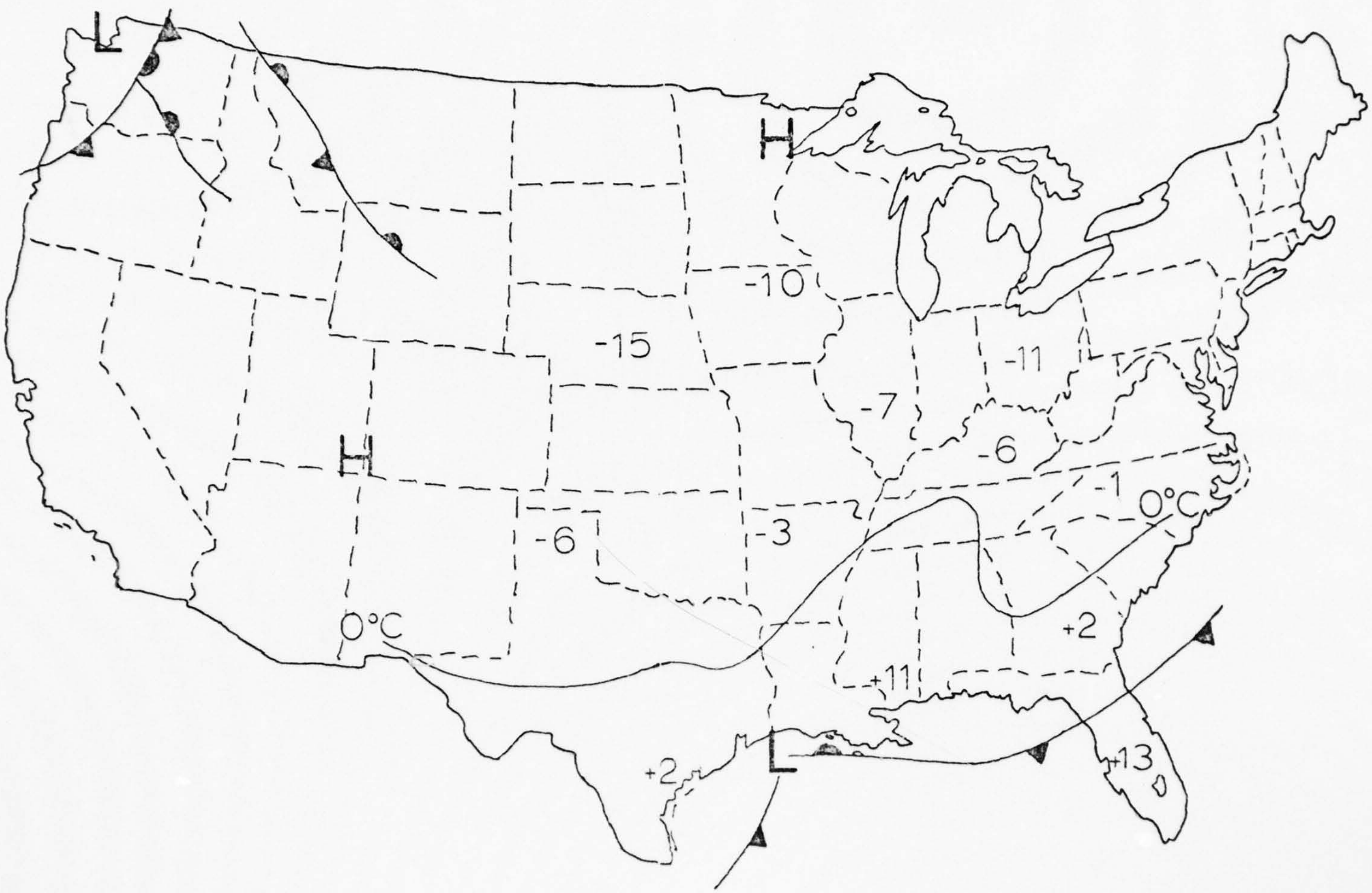

Fig. 6. Synoptic map for 9 January 1968 (1200 GMT). Selected surface temperatures are shown in °C. Also the 0°C surface isotherm is indicated for the area of study.

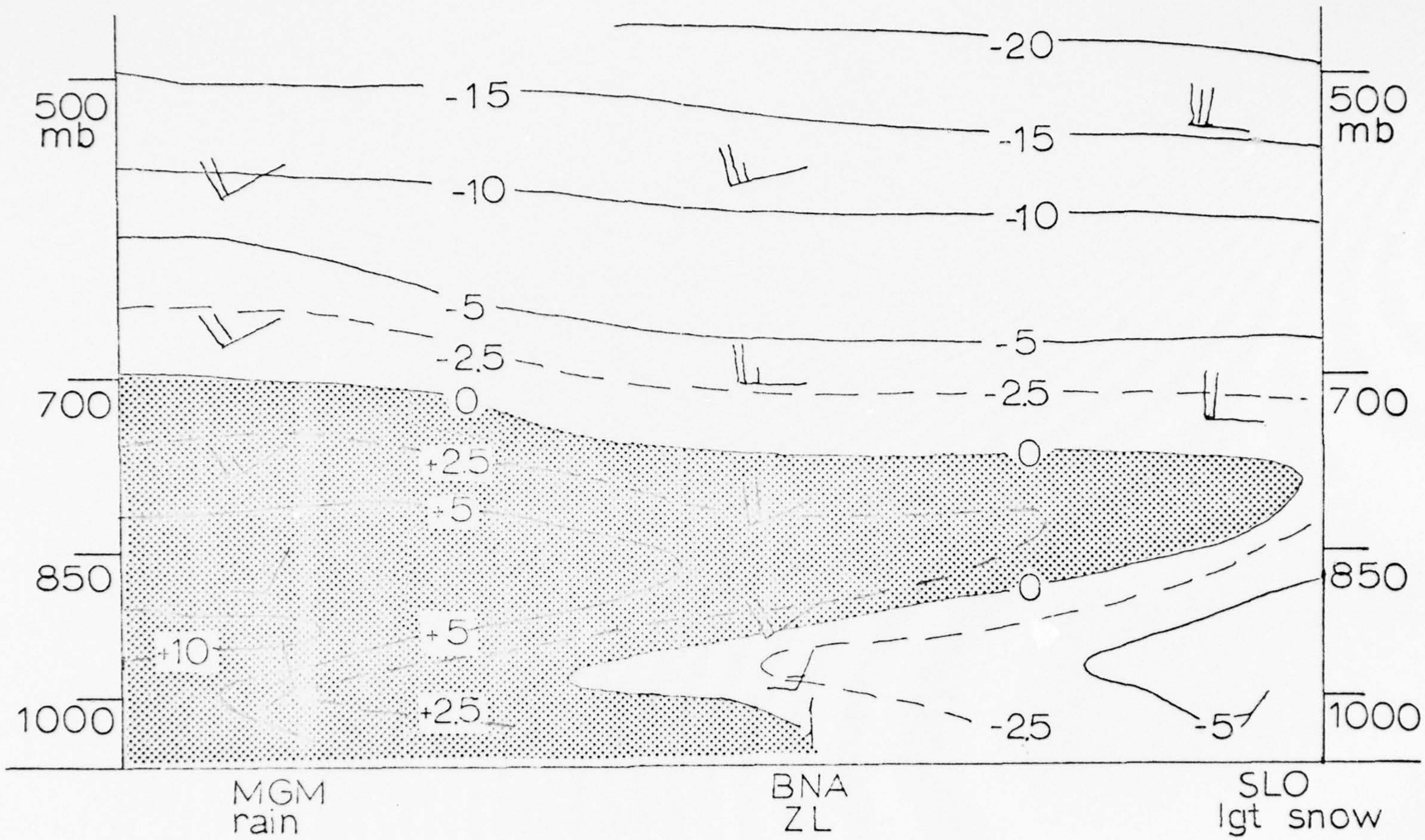

Fig. 7. Vertical cross section for 9 January 1968 (1200 GMT) from Montgomery, Alabama, to Salem, Illinois. All temperatures are in °C and warm air (above °C) is shaded.

cipitation over the next few days. On 12 January a particularly strong wave developed and moved up the east coast thereby producing freezing rain and snow. Temperatures in the South and Southeast began a slow warming trend beginning on the 13th.

3. Location of freezing precipitation areas

Some freezing precipitation was falling early on the 6th along the Appalachians and affecting Atlanta and Nashville although surface temperatures throughout the area remained mostly above freezing and thus were too warm for any extended occurrence. By the 7th, surface temperatures had dropped considerably, and the 0° C isotherm stretched from south of Atlanta to Birmingham to Jackson (Mississippi) and then southwestward to Corpus Christi. However, favorable conditions of overrunning were not well established. By late on the 8th and early on the 9th, conditions changed and an extensive shield of precipitation extended over the area, with bands of freezing precipitation from Dallas to near Memphis and again along the Appalachians.

As the low in the Gulf deepened and moved slowly in the next 24 h, the freezing precipitation band from Dallas to Memphis remained nearly stationary and widened. At the same time, temperatures along the Appalachians rose enough to change most of the freezing precipitation occurrences to rain (see Fig. 8 for areas involved). As the wave moved out of the area, freezing precipitation other than isolated occurrences ceased until early on 12 January, when in conjunction with another developing wave, freezing precipitation once

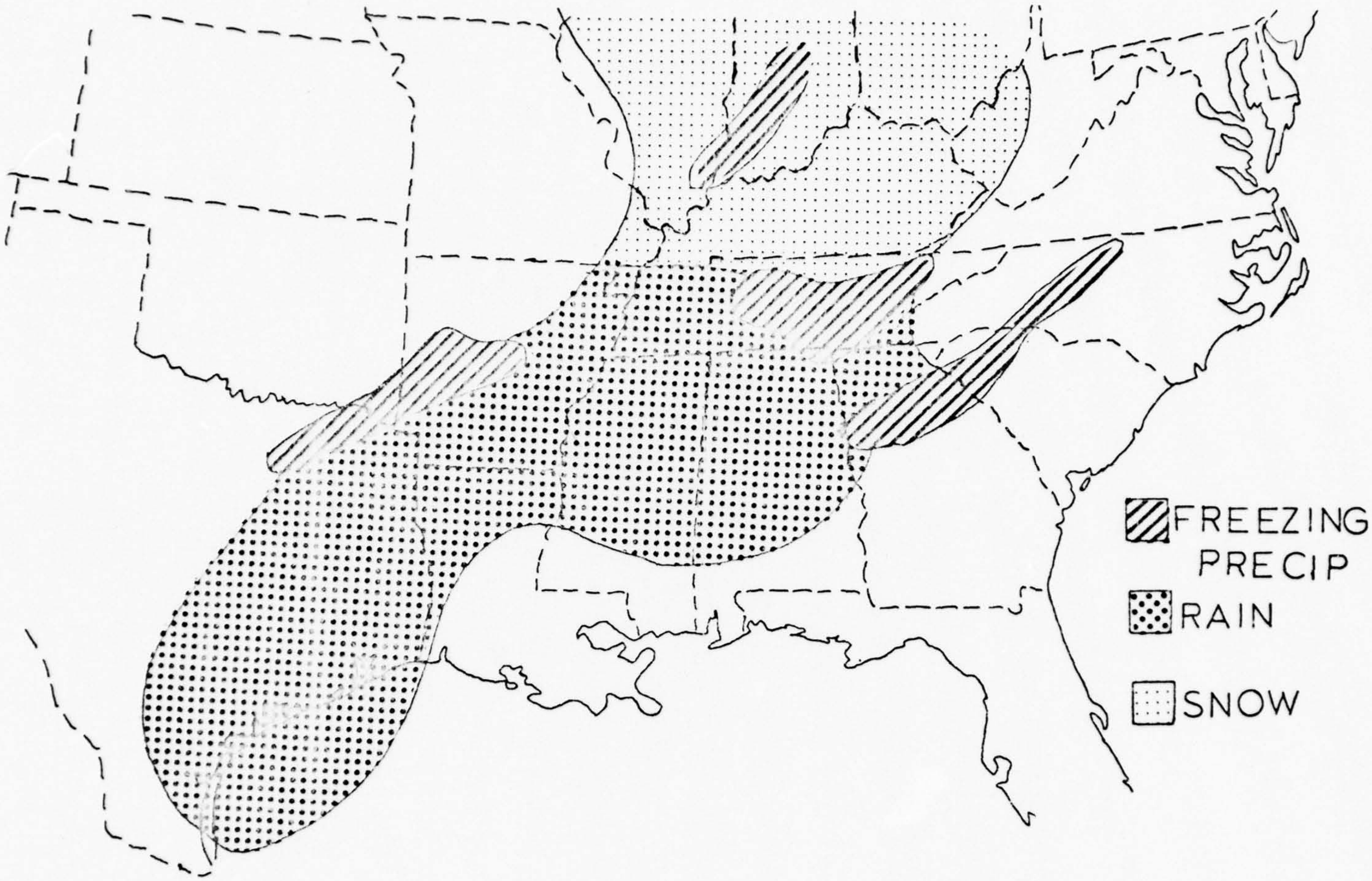

Fig. 8. Areas of precipitation in southeastern United States on 9 January 1968 (1200 GMT).

again occurred around Little Rock and in the vicinity of the southern Appalachians. Effects of this wave reached a peak on the 13th mainly in Georgia, eastern Tennessee, and the Carolinas with Macon and Atlanta (in Georgia) and Greenville and Charlotte (Carolinas) among the cities most affected. After this date, the storm continued up the east coast cutting off the moisture and overrunning warm air sources from the area and effectively ending the ice storm in the area.

B. Storm of 7-8 January 1973

1. Effects on area, and background

Much has been written about the damage produced by this tremendously destructive storm. A particularly good account is given by Ludlum (1974). States affected heavily included New Mexico, Texas, Oklahoma, Missouri, Arkansas, Louisiana, Tennessee, Mississippi, Alabama, Georgia, and South Carolina. The most spectacular damage occurred in northern Georgia, where freezing rain fell nearly continuously for 36 h or more and damages were well over $25 million, but Mississippi, Alabama and Louisiana all suffered heavy monetary loss, especially in the northern portions of those states. Many schools were out from 1-4 d and power and communications were disrupted for long periods in many rural communities and even some of the larger cities (especially Atlanta). In general, this storm is usually considered to be the most destructive of its kind in history.

2. Development

On 1 January 1973 a frontal boundary extended from New England SSW into the Gulf of Mexico with a second front just entering the west coast north of Vancouver Island. Temperatures in the South and Southeast were generally warm and some rainfall amounts at this time were fairly heavy. Over the next 2-3 d, the front in the Northwest moved southeastward and proved to be a good snow producer while a high began to build west of Hudson Bay in Canada. By the 5th of January, the front had moved to the coast of the Gulf of Mexico with spotty freezing precipitation along its boundary as the first surge of cold air behind it dropped temperatures drastically in the South and Southeast. But the coldest air was yet to come since the main high-pressure center at this time was south of Great Slave Lake in Canada. Central pressure over the next 24 h built to 1039 mb.

By 1200 GMT on 7 January, the front was in the Gulf of Mexico stretching from northern Florida to a wave in the western Gulf off Houston and then to the SSW. The cold air had penetrated farther southeastward and the period of heaviest freezing precipitation had begun. During the next 36-48 h, the front remained fairly stationary with minor waves moving ENE along its boundary and producing considerable overrunning through the entire Southeast. The high at this time was centered in North Dakota and moving slowly SSE with strong ridging to the south into central Texas and southeastward into the Carolinas (see Figs. 9 and 10 for synoptic situation and representative vertical cross section).

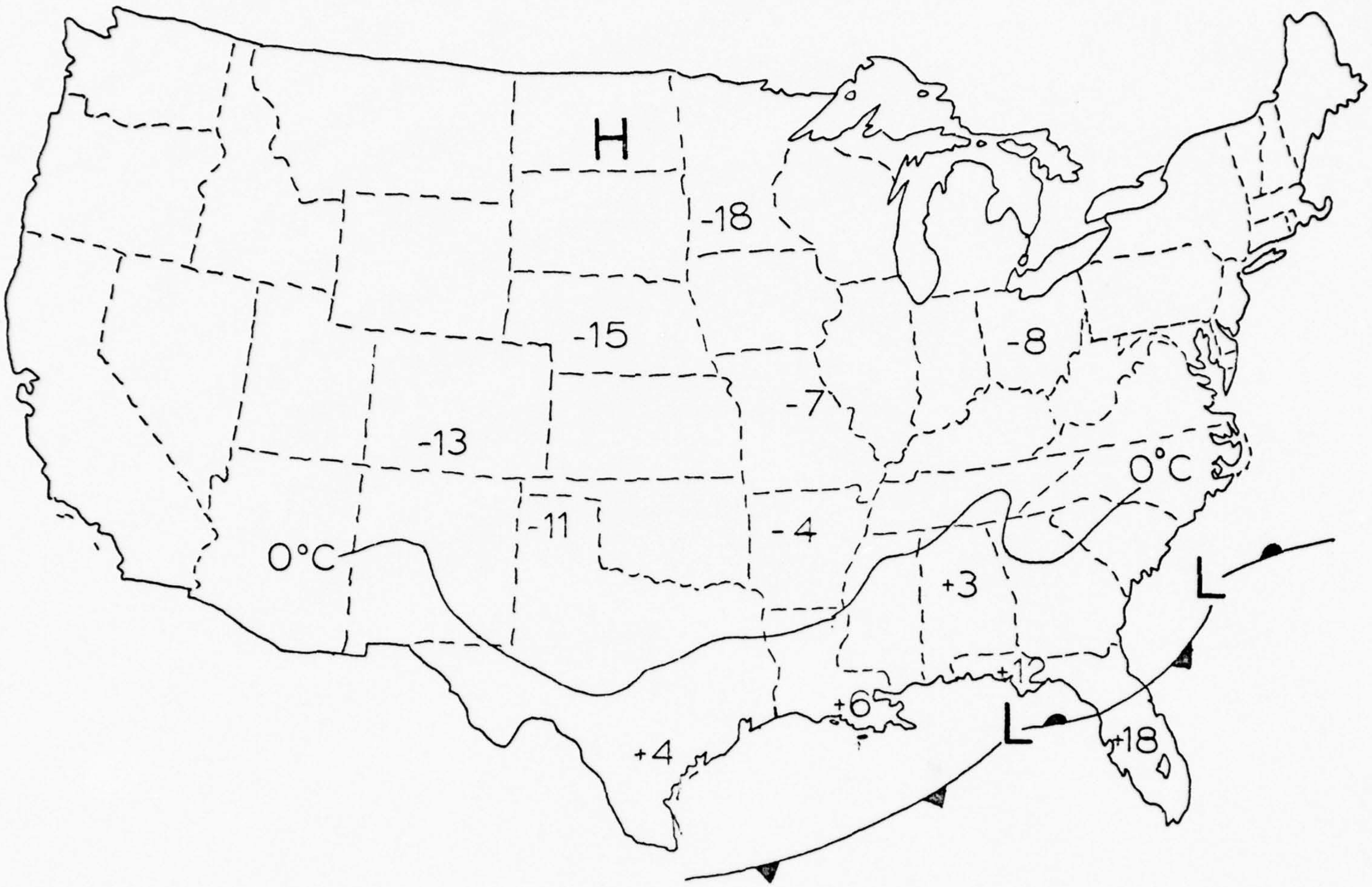

Fig. 9. Synoptic map for 8 January 1973 (0600 GMT). Selected surface temperatures are shown in °C. Also the 0°C surface isotherm is indicated for the area of study.

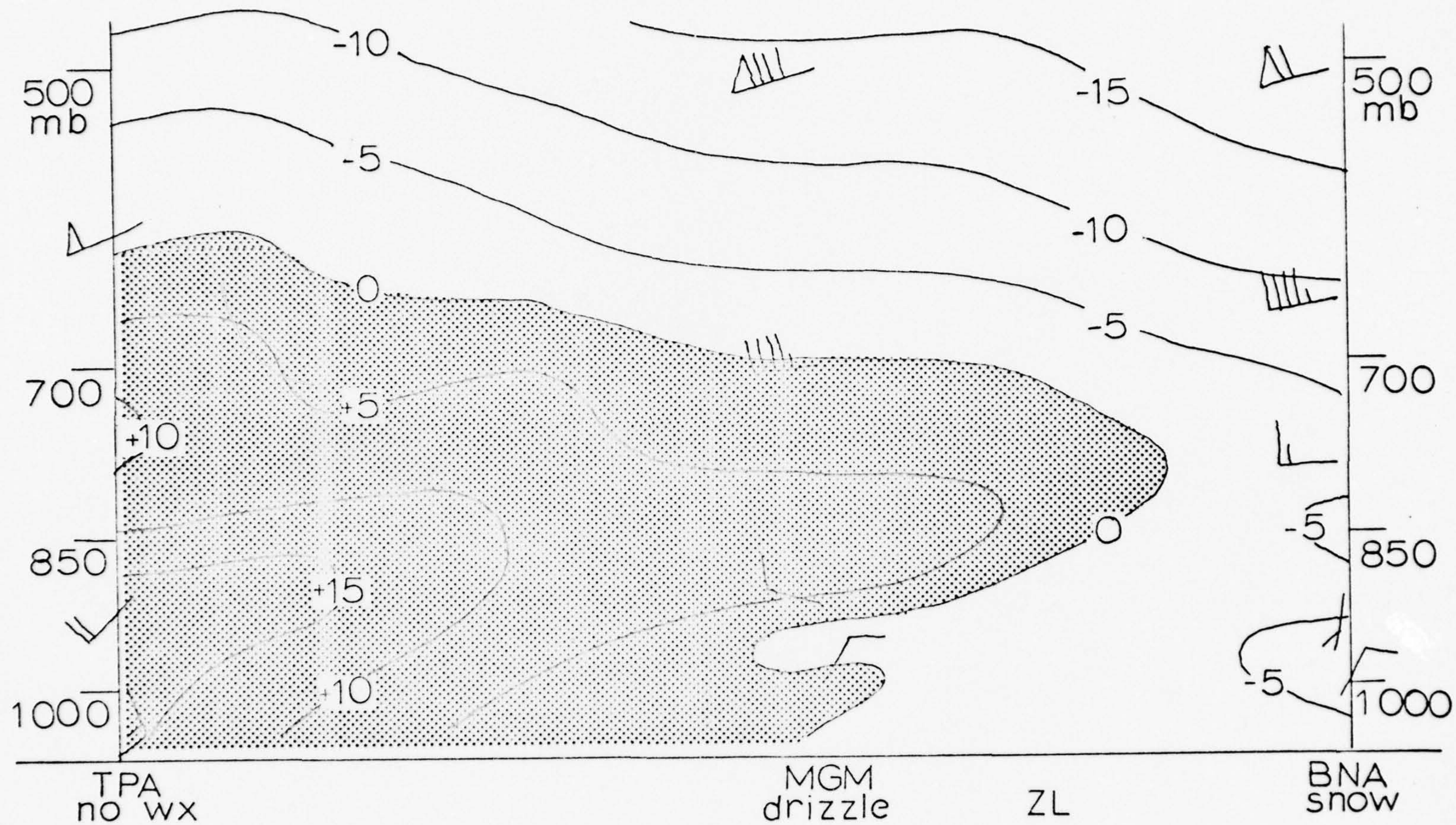

Fig. 10. Vertical cross section for 8 January 1973 (1200 GMT) from Tampa, Florida, to Nashville, Tennessee. All temperatures are in °C and warm air (above 0°C) is shaded.

Intensity of the storm finally began to diminish only as the cold air pushed the front deeper into the central Gulf and became so deep over the area that in most areas freezing precipitation became no longer possible. The frontal boundary eventually moved off to the east by 12 January and the area very slowly began to warm again.

3. Location of freezing precipitation areas

By early morning on 7 January, spotty freezing precipitation was occurring in northern Georgia and eastern Tennessee. By 1800 GMT, the surface 0°C isotherm extended from Greenville, South Carolina, WSW across northern Mississippi and into northeastern Texas passing just south of Abilene (Fig. 9). A well-defined band of freezing precipitation and sleet extended from Shreveport to Chattanooga with a second area west and northwest of Dallas also heavily affected. As waves moved along the frontal boundary in the Gulf over the next 24 h, the areas of freezing rain vascillated to the north or south but retained their identities fairly well. During this period, the southern half of Arkansas, most of Tennessee, and the northern halves of Mississippi, Alabama, and Georgia were affected particularly heavily (Fig. 11). Harms (1974) noted that, "... the freezing rain band was approximately 60 n mi in width, occurring just south of the 850 mb 0°C isotherm which remained nearly stationary along the northern Georgia border." This helps account for the especially heavy accumulations in that area.

By midday on the 8th, the bands of freezing precipitation were nearly dissolved and only isolated occurrences were noted (Ft. Smith,

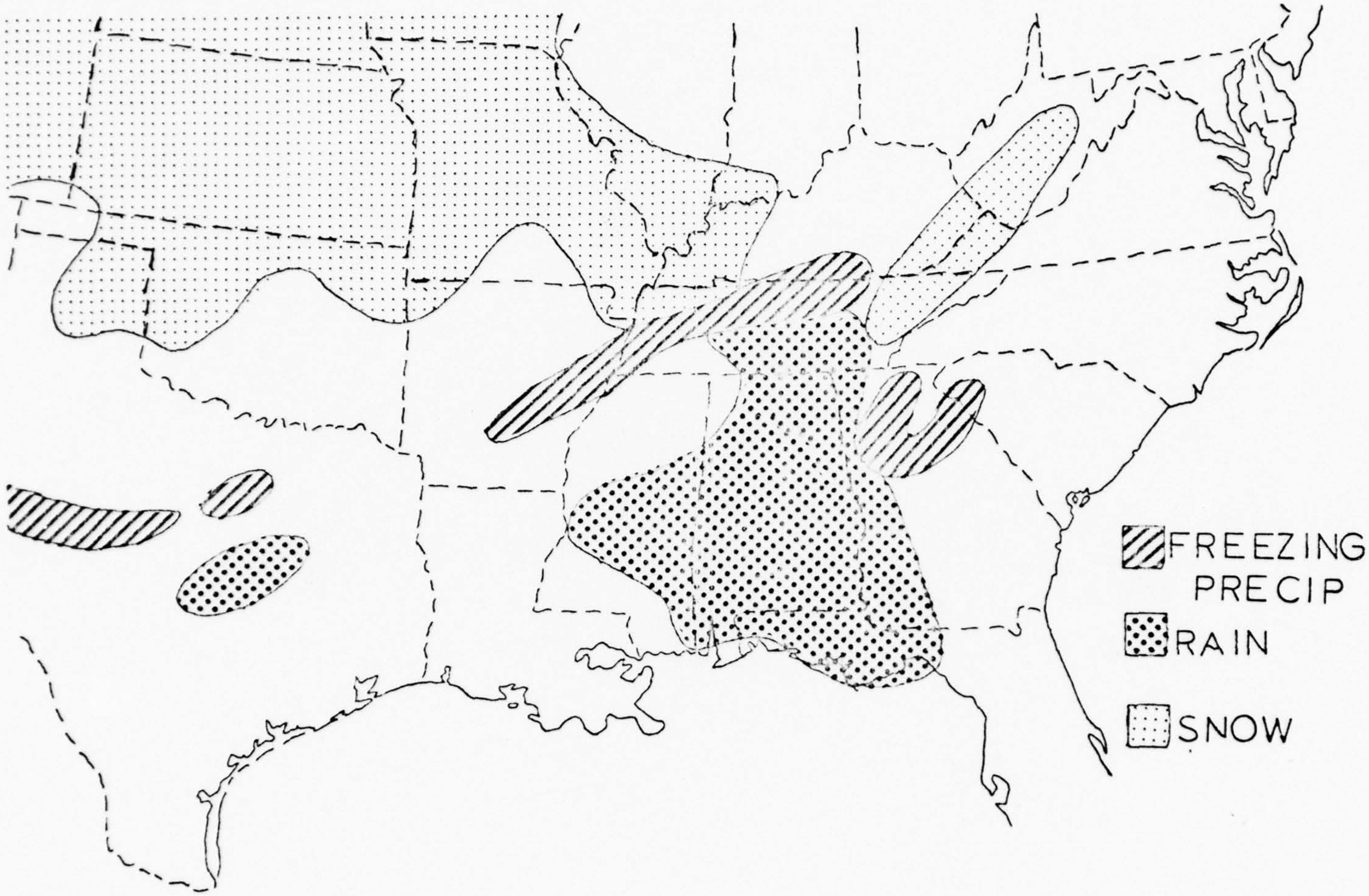

Fig. 11. Areas of precipitation in the southeastern United States on 8 January 1973 (0600 GMT).

Arkansas; Jackson, Mississippi; Atlanta, Georgia, among others). By late afternoon, only very isolated reports remained.

During the storm, several cities endured prolonged periods of freezing precipitation (some as long as 24 or more continually). A few of the cities thus affected were Atlanta, Memphis, Nashville, Muscle Shoals (Alabama), Little Rock, and towards the end of the storm, Jackson, Mississippi.

C. Storm of 8-9 February 1973

1. Effects on area, and background

The storm of 8-9 February 1973, although in itself fairly light in intensity, was memorable for several other reasons. First it occurred only about a month after the worst (or at least one of the worst) storms ever to affect this area, and second because it was the prelude to one of the heaviest snowstorms ever to strike the South (see either Hodge, 1973, or Tang, 1974, for more in regard to the snowstorm).

Most of the real damage produced by the ice storm was limited to the southern half of three states--Louisiana, Mississippi, and Alabama. Over $500,000 in damages resulted in Louisiana and over $600,000 in Alabama. Hardest hit of the three was Mississippi where approximately a million dollars in damage occurred over a 4-d span from 7-10 February. As the storm moved along the east coast, the Carolinas also were heavily damaged due to freezing precipitation (in combination with the heavy snows which followed). In that area, over $3 million in damages resulted, much associated with the poultry

industry.

2. Development

A good description of the meteorology of this storm is presented by Hodge (1973). A second discussion can be found in the article by Harms (1974). Although they were concerned more with the snowstorm which followed and its destructive properties, they do include quite detailed information in regard to the freezing precipitation and sleet which fell earlier in the storm. Much of the basic information used in this paper with respect to this storm comes from their work along with that of Tang (1974).

Once again, the pattern involved a building, winter, high-pressure system (in Alaska on 3 February) and a Pacific storm front which caused heavy rains and storms as it made its way across the continent. By 5 February 1973, the high had built to 1052 mb in the Mackenzie River Basin (in Canada)aand the front reached the Rocky Mountains. As an indication of how cold the air to the north was, the temperature at Great Falls, Montana, had dropped to -46°C by early on the 7th.

By morning (1200 GMT) on 8 February 1973, the cold front extended from New York State SW across eastern Tennessee, diagonally across Alabama into the Gulf of Mexico, and then inland again just north of Brownsville, Texas. The cold high behind it was then centered in southern Montana with ridging to the SE. The cold front had been moving very rapidly and temperatures dropping dramatically behind it. Temperatures as far south as Oklahoma and northern

Arkansas were between -5 and -10° C at this time.

By that evening, the front extended from the eastern slopes of the Appalachians SSW through eastern Georgia and the Florida panhandle and into the Gulf of Mexico. The high had slowed in its drive southeastward and was now centered in Wyoming. Air temperatures were then less than 5° C almost everywhere behind the front (although it did take a while longer for the actual ground to become this cold since it had been so warm prior to frontal passage). High pressure east of Florida also had been building up, thus setting up nearly ideal conditions for warm, moist air to overrun the frontal boundary in the Gulf.

A low formed on the 8th and by 1200 GMT on the 9th was well-defined on the frontal boundary in the western Gulf. Its location at this point was approximately due south of New Orleans and due east of Brownsville (see Figs. 12 and 13 for synoptic situation and representative cross section). The peak of the ice storm occurred near this time, for as the wave deepened and moved off to the ENE, the cold air continued to push strongly SSE and drop temperatures further to the point where it was too cold for more freezing rain to fall. At this time, the low continued to move more NE and pulled the frontal boundary with it out of the Gulf by late on the 9th. This differs significantly from the previous two storms discussed (January 1968 and January 1973) in that the frontal boundary did not remain nearly as long in the Gulf. This precluded the formation of a series of waves that could move along the front and block the rapid southward penetration of the cold air. Instead the cold air

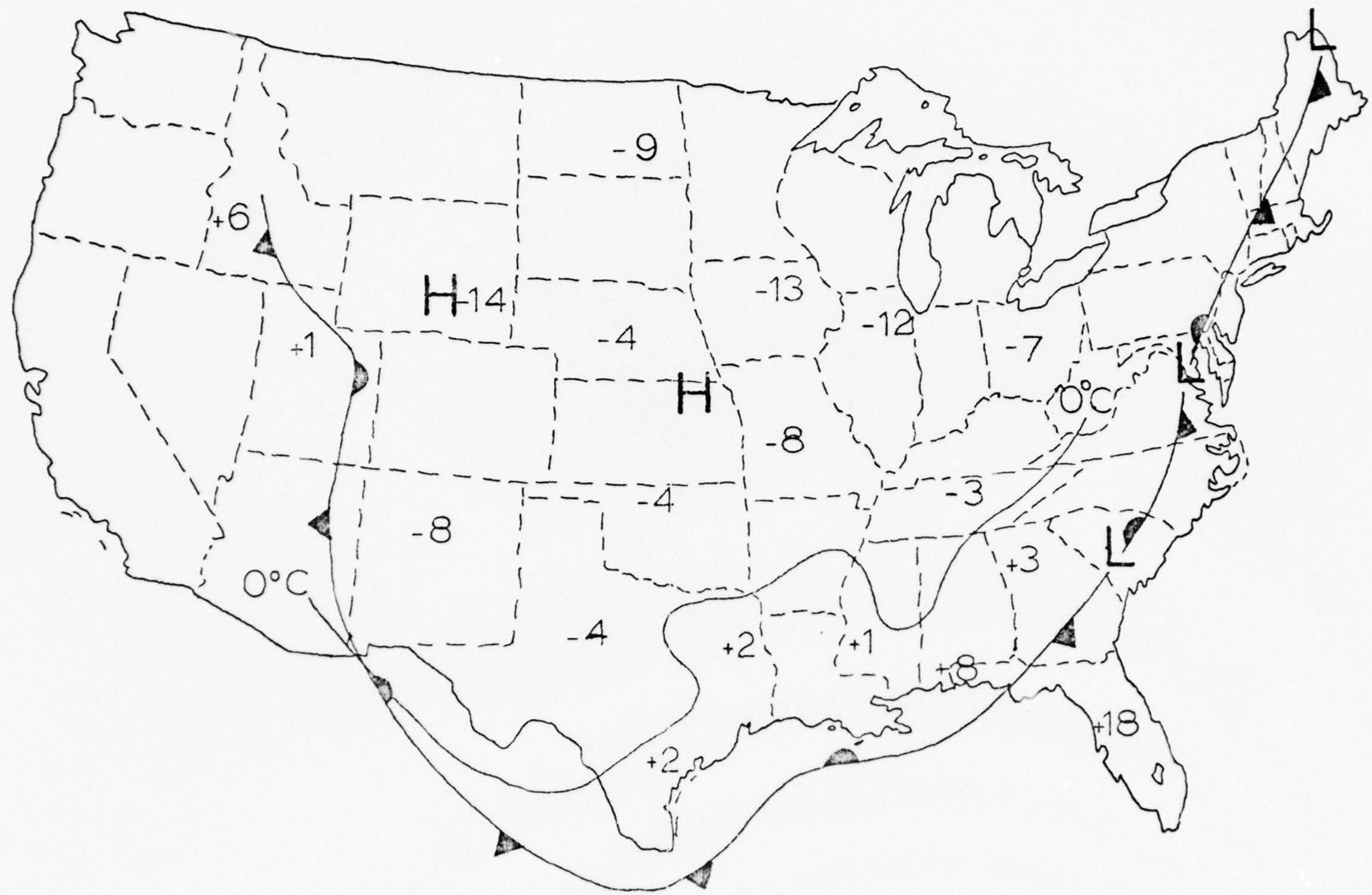

Fig. 12. Synoptic map for 9 February 1973 (0000 GMT). Selected surface temperatures are shown in °C. Also the 0°C surface isotherm is indicated for the area of study.

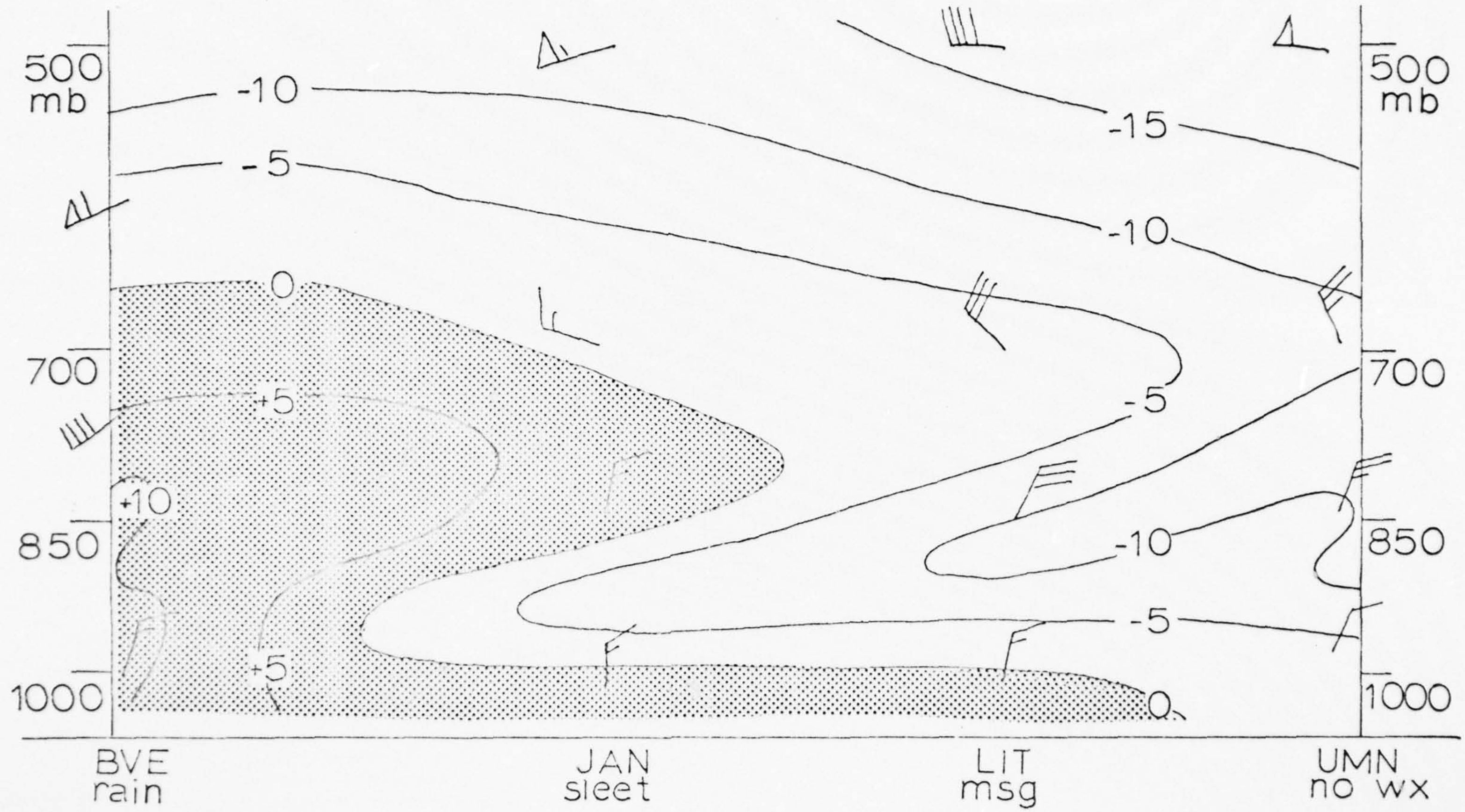

Fig. 13. Vertical cross section for 9 February 1973 (0000 GMT) from Boothville, Louisiana, to Monett, Missouri. All temperatures are in °C and warm air (above 0°C) is shaded.

continued to drive south while the low in the Gulf deepened more rapidly and moved out, thus resulting in overall colder soundings and more snow than freezing precipitation.

Satellite photos of the Gulf of Mexico on 10 February showed well-defined "cloud streets" in the central Gulf where the very cold air was being modified by the warm waters. The storm continued to develop and eventually moved up the east coast while the temperature over the southeast very slowly modified (temperatures were between -5 and -10°C throughout this area the night of the 10th and reached only +5°C at a few places on the 11th).

3. Location of freezing precipitation areas

To quote Hodge (1973), "Freezing rain fell for the longest time at coastal locations such as Victoria, Texas; Pensacola, Florida; Beaufort and Myrtle Beach, South Carolina; and Jacksonville, North Carolina. In Louisiana freezing rain fell for more than 5 hours at Alexandria."

Effects of the ice storm were felt in Kansas on the 7th and spread into Missouri and Oklahoma by that evening. Some stations affected during the early stages of the storm were Dodge City (Kansas), (Kansas), Joplin and Springfield (Missouri), and Tulsa (Oklahoma). Early on the 8th, spotty freezing precipitation and sleet began falling in Arkansas and northeastern Texas with heavier amounts falling by midday as the storm spread into east central Texas, central Louisiana, and central Mississippi. Stations affected at this time for extended periods (periods in excess of 1 h) were Victoria and

Houston (Texas), Lafayette (Louisiana), and McComb (Mississippi).

The heaviest part of the ice storm occurred from about 0000 GMT to about 1200 GMT on the 9th affecting most of the Gulf Coast from Victoria to Pensacola (Fig. 14). Cities heavily affected included Harlingen, Texas; Covington, Louisiana; Biloxi, Mississippi; Jackson, Mississippi; Mobile, Alabama; Abbeville, Alabama; Eufaula, Alabama, and Pensacola, Florida.

Some areas, particularly from the Florida panhandle eastward, continued to get freezing precipitation after this time, but for most of the western Gulf, the ice storm was over. Florida, South Carolina, and North Carolina continued to feel the effects of the storm through midmorning on the 10th with some places (such as Jacksonville, North Carolina) being hit very hard.

D. Storm of 22-24 January 1977

1. Effects on area, and background

This storm could be labeled as being of light intensity, perhaps even lighter than the storm in February 1973 (discussed previously). A storm earlier this month did much more monetary damage (2-3 January affecting mainly Arkansas, Louisiana, and parts of Mississippi, Alabama, and Georgia; damages from this storm were in excess of $6 million dollars and there were several storm-related deaths). However, a fair amount of freezing precipitation did fall between the 22nd and the 24th mainly over an area which included most of Arkansas, southern Missouri, Kentucky, parts of Tennessee, Louisiana, and Mississippi, and northern Alabama and Georgia (with

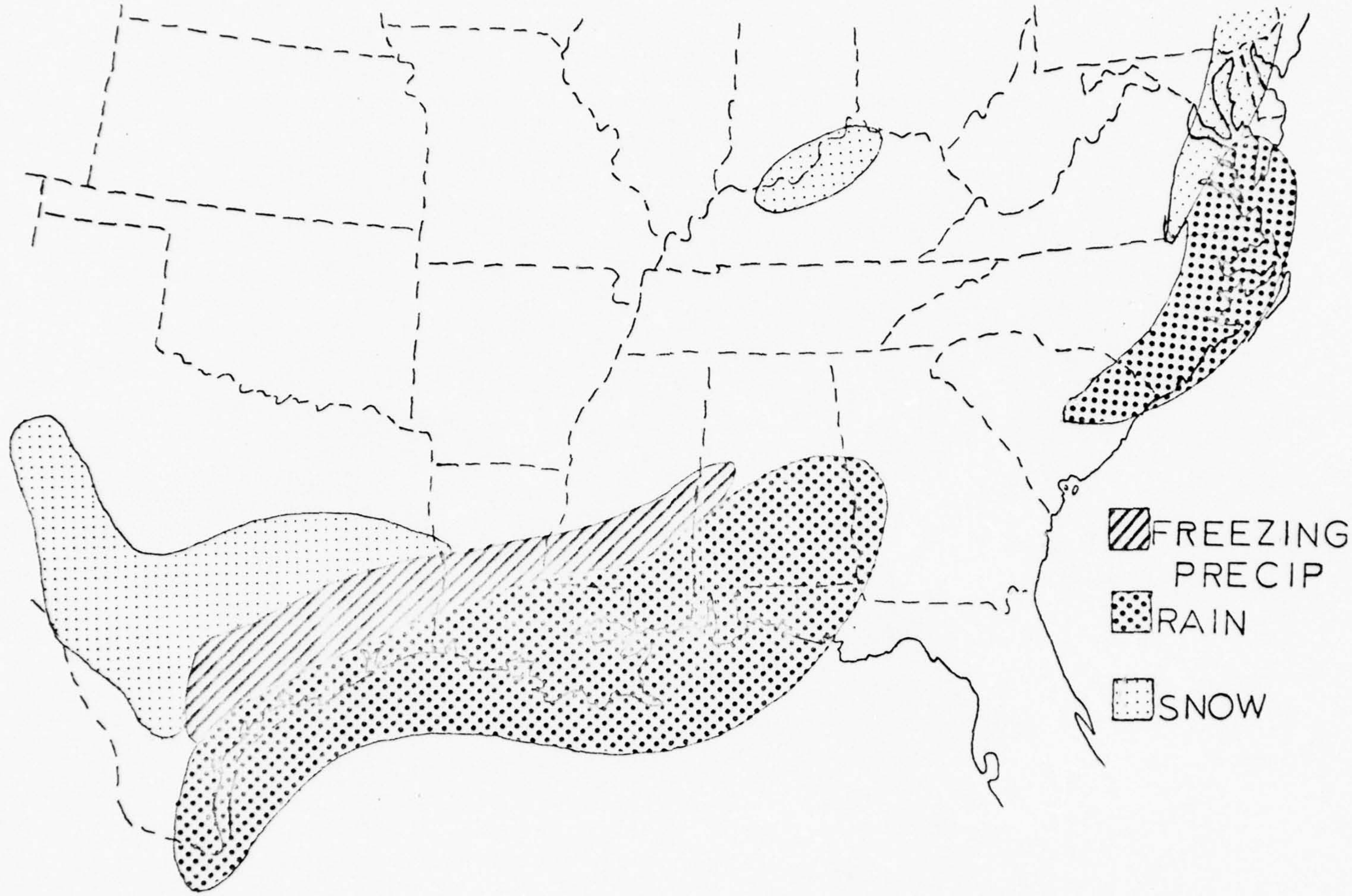

Fig. 14. Areas of precipitation in the southeastern United States on 9 February 1973 (0300 GMT).

Atlanta once again receiving freezing precipitation over a prolonged period). No totals of monetary damage to the area were available but cities reporting freezing precipitation for periods in excess of 1 h (besides Atlanta) included Paducah, Kentucky, Ft. Smith and Little Rock, Arkansas.

2. Development

This storm was selected because it differed somewhat in terms of development, from the previous three storms discussed, particularly in the later stages. Once again the source of cold air was a high-pressure system which had built in Canada and moved southeastward into the north-central United States. The frontal boundary itself moved into the west coast on the 21st and by 0000 GMT on the 23rd extended from central Canada SSW into central Nebraska then SW into the Oklahoma panhandle. High pressure was building in British Columbia while the high preceding the front moved ESE into southern Indiana. At this time, freezing precipitation was falling in Nebraska and Kansas ahead of the cold front.

As the high moved off towards the central east coast during the next 24 h, the return flow in the western Gulf of Mexico generated a frontal wave off the Texas/Louisiana coast. This established a favorable overrunning pattern, particularly with regard to northern Louisiana, Arkansas, northwestern Mississippi and western Tennessee. During this period, the front in the central United States continued to push ESE so that by 1200 GMT on the 24th, one frontal boundry extended from Michigan SSW through western Kentucky to a low in

Tennessee and then south into the Gulf with a warm front roughly along the northern border of the Florida panhandle. With strong ridging behind it, the frontal system continued to push eastward (the southern half progressing more rapidly than the northern half) and as a result the storm weakened considerably by 2100 GMT on the 24th except for isolated occurrences of freezing precipitation.

Main differences with respect to this storm (as opposed to the previous three) were that much of the freezing precipitation that fell occurred ahead of the advancing cold front (instead of the more favorable position ahead of an advancing warm front) and the more easterly push of the entire frontal boundary throughout the storm. However, the common elements of a deep cold high forming in Canada and a wave forming in the western Gulf of Mexico did exist and played a major role in the storm's development (see Figs. 15 and 16 for synoptic situation and vertical cross section at peak of storm activity).

3. Location of freezing precipitation areas

Midday on 22 January, freezing precipitation was falling in parts of Nebraska and much of Kansas with areas of snow and ice pellets also occurring behind a band of moderate rainfall. By nightfall, the rain and isolated occurrences of freezing precipitation had spread ahead of the slow-moving cold front into southwestern Missouri, most of Arkansas, and extreme western Tennessee. As the 23rd progressed, freezing rain touched parts of Louisiana and Mississippi by 1100 GMT, Kentucky by 1300 GMT, and central Tennessee by 1900 GMT.

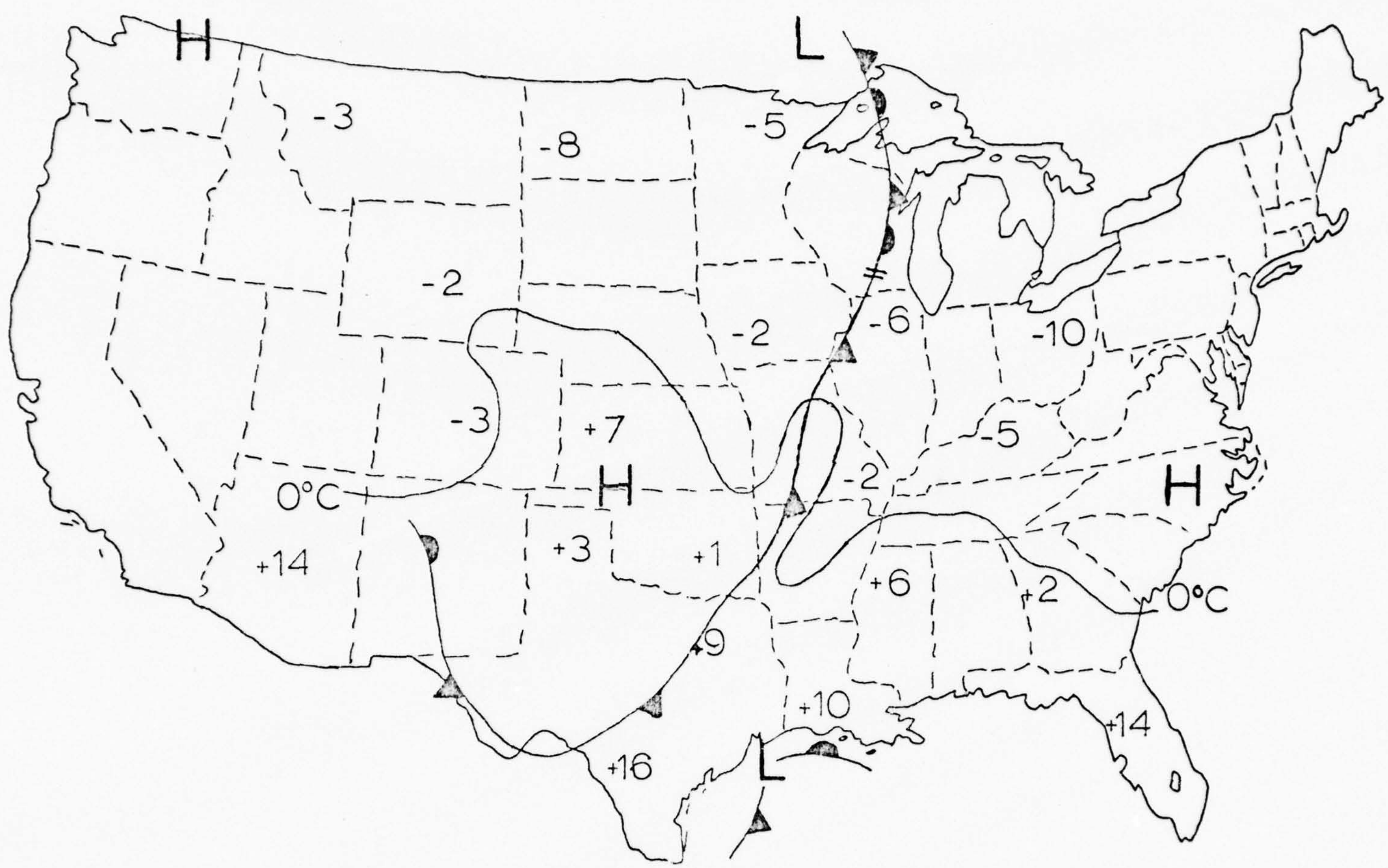

Fig. 15. Synoptic map for 23 January 1977 (1800 GMT). Selected surface temperatures are shown in °C. Also the 0°C surface isotherm is indicated for the area of study.

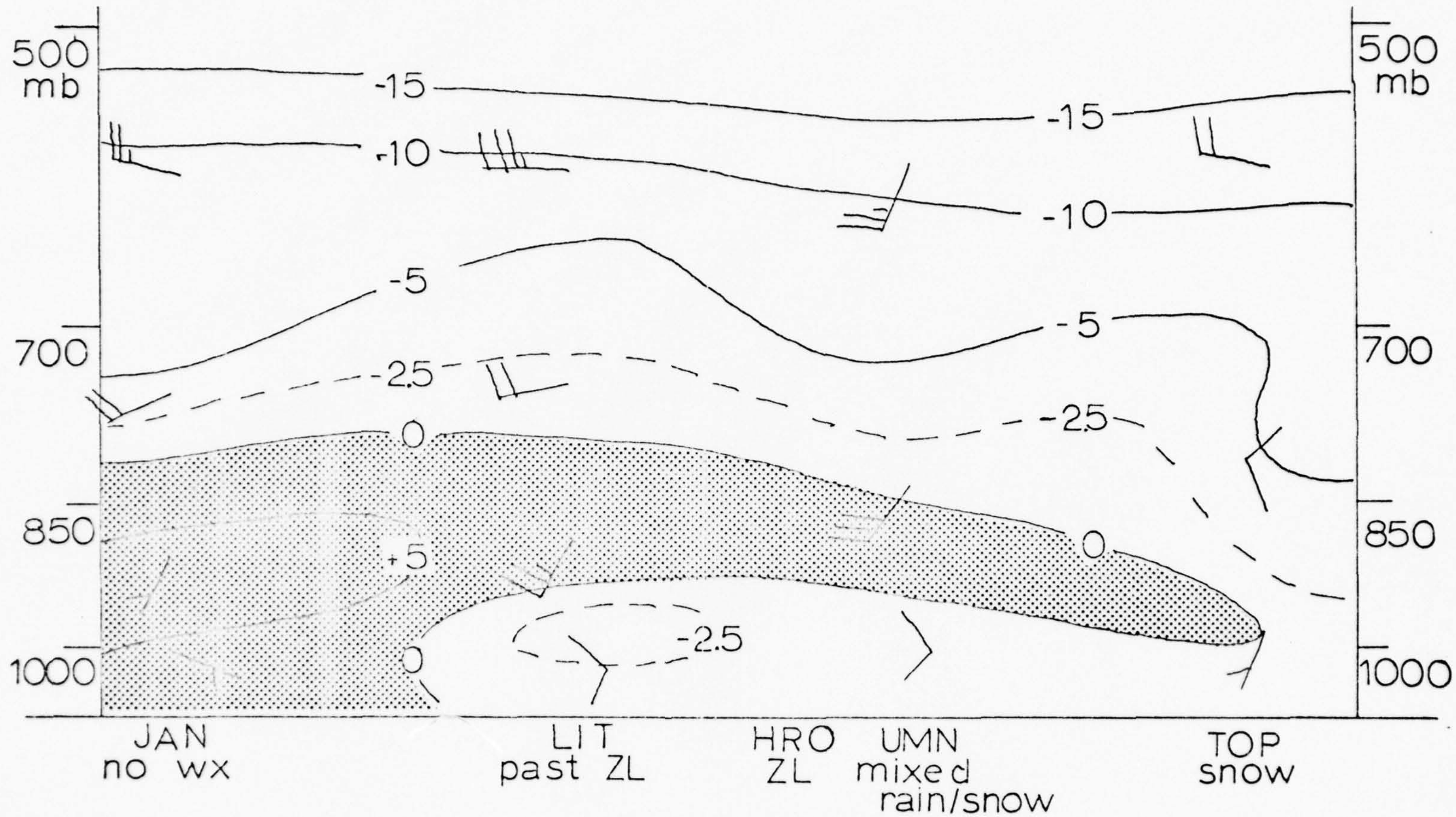

Fig. 16. Vertical cross section for 23 January 1977 (1800 GMT) from Jackson, Mississippi, to Topeka, Kansas. All temperatures are in °C and warm air (above 0°C) is shaded.

As the wave in the Gulf developed, the precipitation shield in the south expanded, although for the most part this consisted of rain and rainshowers, but freezing precipitation continued to fall in spotty locations at 0300 GMT on the 24th. Among the areas affected at this time were central Kentucky and Tennessee, and northern Alabama and Georgia. By 1000 GMT, freezing rain was falling in Atlanta and continued to fall until after 1700 GMT. Also that morning, overrunning conditions developed with the wave in the western Gulf, so once again freezing precipitation spread into Arkansas, particularly the south and central portions (see Fig. 17 for freezing precipitation areas). The wave progressed ENE into southern Mississippi and central Alabama during the next 24 h, coupled with the other frontal boundary, and spread warmer air into the central Gulf coast states. As a result the freezing precipitation areas were reduced with only isolated occurrences remaining in the area by that evening.

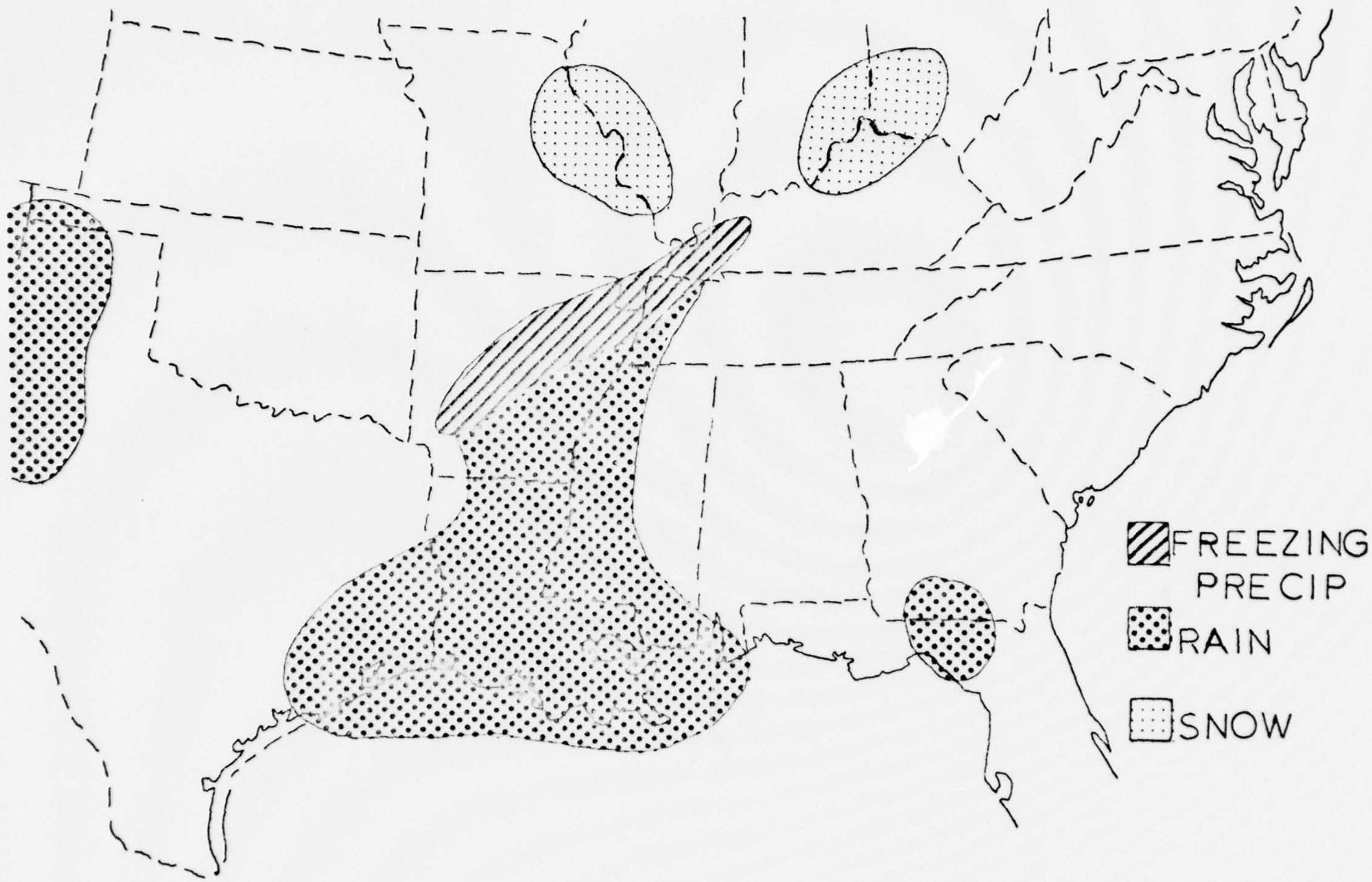

Fig. 17. Areas of precipitation in the southeastern United States on 23 January 1977 (1800 GMT).

IV. ANALYSIS OF PARAMETERS FOR SELECTED STORMS

A. General discussion

The first approach to handling the data from the individual storms was to show the parameters for each, individually. However, since there are a limited number of radiosonde stations available in the area under study (11), it proved very difficult to obtain a representative sampling of upper-air data (especially those stations reporting freezing precipitation) for each storm. Thus it was decided to group all the data obtained from the four storms into one sample and to present the results collectively. This was felt to be a fair approach since the storms were basically alike (cold air from the northwest forming a wedge beneath warm, moist air supplied from the Gulf of Mexico), although variations in exact synoptic situation (and thus location and intensity of resulting freezing precipitation bands) did exist.

Also, note that for all surface parameters discussed, the sample size will be larger than for the upper-air parameters. This is because nonradiosonde stations which received freezing precipitation were included to enlarge the sample size.

B. Surface parameters

1. Temperature

A graph of surface temperature vs number of occurrences is presented in Fig. 18. The study was done in Fahrenheit and then converted to temperatures to show better detail. Of particular

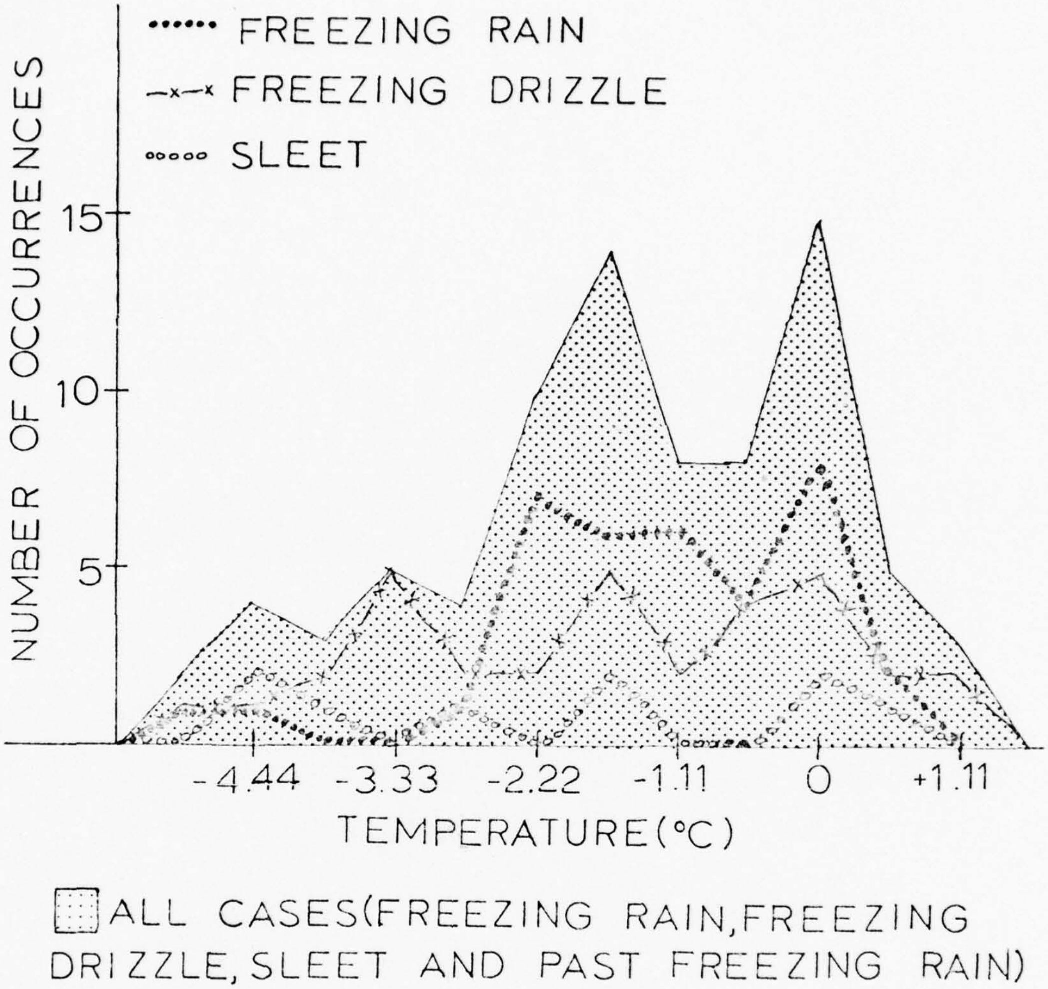

Fig. 18. The number of occurrences of freezing precipitation (various forms) over a range of surface temperatures (°C). Study originally accomplished in °F. Data from selected storm cases.

interest, 31 out of 36 occurrences of freezing rain are in the narrow range between -2.22 and 0 degrees Celsius, inclusive. The spread for the occurrence of freezing drizzle was much larger, as it extended from -5 to +1.11 with one case occurring at -12.78°C. This broader range also holds for the occurrence of sleet.

Table 2 shows the means, modes, and medians of all 82 cases of freezing precipitation (cases of freezing rain, freezing drizzle, past freezing rain, and sleet), freezing rain alone, freezing drizzle alone, and sleet alone.

2. Dew Point

A graph of surface dew point vs number of occurrences is presented in Fig. 19. Although the range of dew-point temperatures with respect to occurrences of freezing rain is not as narrow as was the case with surface temperature, it still is quite well defined. Thirty-four out of 36 cases fall between -3.89 and 0°C. Freezing drizzle and sleet also show much wider ranges of dew-point temperatures. From the mean values for surface temperature and dew point, an average temperature - dew point spread for freezing rain would be about 1 deg Celsius. Mean, mode and median values of dew point are once again presented in Table 2.

3. Wind

As would be expected, surface wind proved to be a very variable parameter when considered in light of the total sample. It is, however, a parameter which could prove of some importance if a single

Table 2. Table of means, modes and medians for selected storms (all temperatures in °C).

Parameter	Mean	Mode	Median	Number of Occurrences
Surface Temp				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	-1.55	0	-1.67	82
Freezing rain (66) alone	-1.49	0	-1.11	36
Freezing drizzle (56) alone	-1.78	-	-1.67	34
Sleet (79) alone	-2.04	-	-1.67	9
Surface Dew Point				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	-2.78	-2.78	-2.78	82
Freezing rain (66) alone	-2.53	-2.50	-2.78	36
Freezing drizzle (56) alone	-2.55	-1.67	-2.78	34
Sleet (79) alone	-4.26	-	-3.89	9
850-mb Temperature				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	+2.60	+3.05	+2.78	34
Freezing rain (66) alone	+4.12	-	+3.05	34
Freezing drizzle (56) alone	+1.78	+3.33	+2.78	14
Sleet (79) only	+1.20	+2.78	+1.67	6
850-mb Dew Point				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	+2.09	+3.33	+2.78	34
Freezing rain (66) alone	+3.71	-	+3.05	12
Freezing drizzle (56) alone	+1.11	+3.33	+2.78	14
Sleet (79) alone	+0.83	+0.56	+0.56	6

Table 2. (Continued)

Parameter	Mean	Mode	Median	Number of Occurrences
700-mb Temperature				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	-2.38	-1.67	-1.67	29
Freezing rain (66) alone	-0.69	-	-0.56	12
Freezing drizzle (56) alone	-2.10	-1.67	-1.67	9
Sleet (79) alone	-3.06	-3.89	-3.33	4
850-mb wind direction (degrees)				
All cases rain, snow, drizzle mixed rain/snow, freezing rain, freezing drizzle, sleet and past freezing rain (68, 61, 51, 71, 24, 56, 66, 79)	224.50	230	-	40
Freezing rain (66) alone	211.82	230	-	11
Freezing drizzle (56)	227.5	250	-	8
Averaged 850-mb/700-mb wind direction (degrees)				
All cases rain, snow, drizzle, mixed rain/snow, freezing drizzle, sleet and past freezing rain (61, 71, 51, 68, 66, 56, 79, 24)	234.74	250	-	38
Freezing rain (66) alone	228	230	-	10
Freezing drizzle (56) alone	227.5	230	-	8
1000-to-500-mb Thickness (M)				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	5422.75	-	5415	8
Freezing rain (66) alone	5426.56	-	5420	16

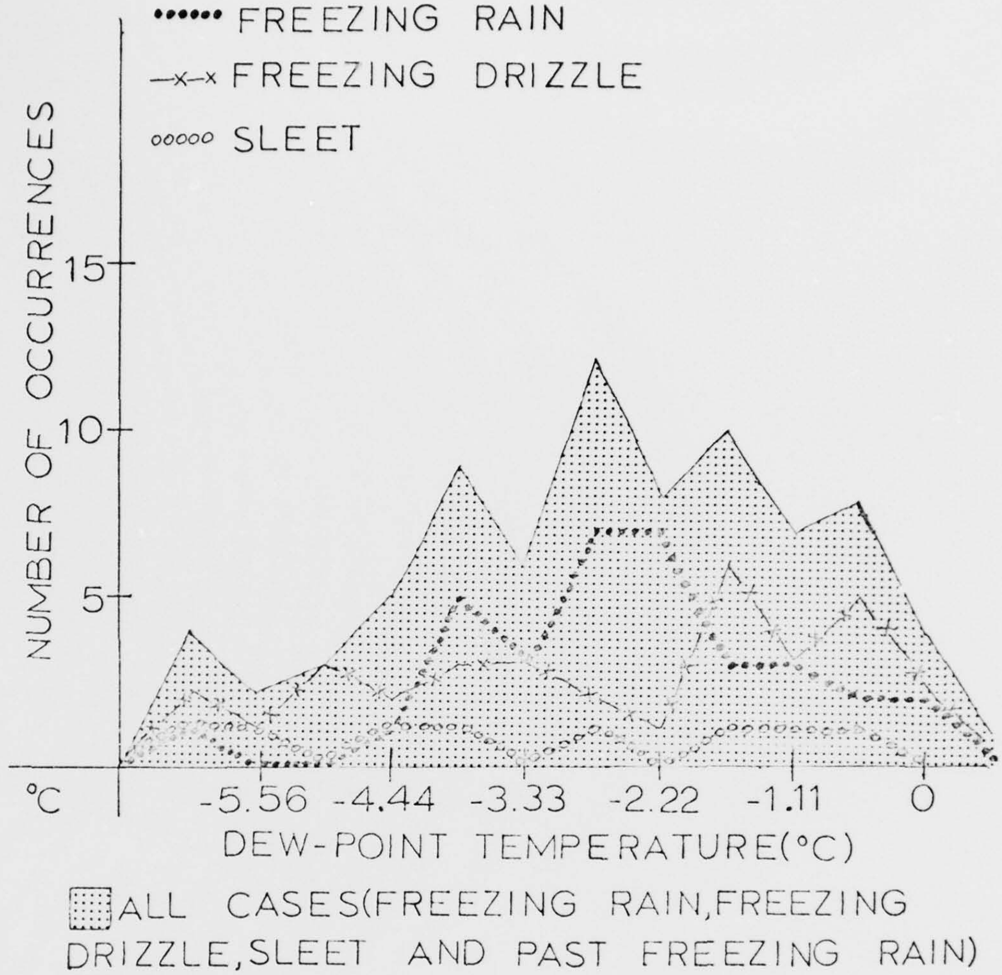

Fig. 19. The number of occurrences of freezing precipitation (various forms) over a range of surface dew points (°C). Study originally accomplished in °F. Data from selected storm cases.

station is onsidered where that station's particular location or topography would influence the storms which occurred in that area. For example, it appears that Atlanta usually has a wind from the east through southeast during periods of freezing precipitation. Particularly favorable wind direction for Atlanta would be between 080 and 110 degrees. In contrast, at Jackson, Mississippi, winds during periods of freezing precipitation appear to be more northerly or northwesterly.

4. Pressure

Another parameter which when looked at with the total sample showed no identifying value or values was station pressure. However, if one remembers that freezing precipitation usually occurs in the area in advance of a warm front (or sometimes ahead of a cold front), then one would expect a drop in pressure before or at the beginning of the precipitation. This proved to be the case for nearly every example studied, although at times the drop was quite small.

5. Visibility

As with rain or snow, visibility during freezing precipitation storms covers a wide range depending to a large degree upon the intensity of the precipitation. Many cases of light freezing rain show visibilities of 11 km or greater whereas visibilities fell below 1.5 km usually only when freezing precipitation was coupled with either fog or snow (or both). Normally visibilities were in the range of 3-8 km.

6. Typical surface plots

In researching the data from the four storms, many plots of surface parameters at single stations were graphed with respect to time. This was accomplished to attempt to locate trends in the parameters discussed previously. Three typical plots of surface parameters are shown in Figs. 20, 21, and 22. They show the progression of the various parameters for about 24 h for each station.

C. Upper-Air parameters

1. 850-mb temperature and dew point

A graph of 850-mb temperature vs number of occurrences is presented in Fig. 23. Once again the most important feature was the relatively narrow temperature range for the occurrence of freezing rain. Eleven of the 12 cases fell in the range between 0 and 6.6°C. The range for freezing drizzle extends into much colder temperatures and produces about a 2.3°C difference in the mean value for the occurrence of freezing rain and freezing drizzle.

Figure 24 shows a graph of 850-mb dew point which shows results similar to those for 850-mb temperature. Table 2 (p. 55) shows the mean, mode, and median values for both parameters.

2. 700-mb temperature

Figure 25 shows a graph of 700-mb temperature vs number of occurrences. The range from -7.78 to +4.44°C hints that although

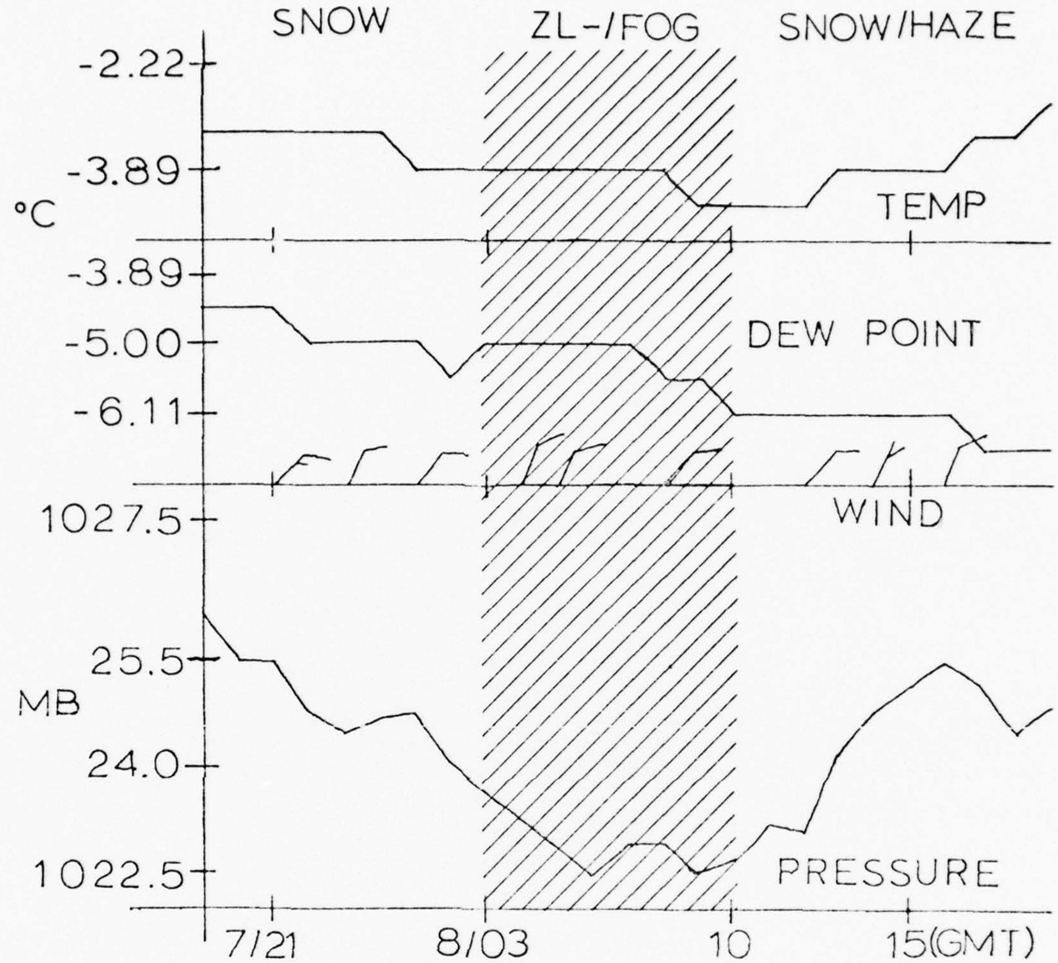

Fig. 20. Surface parameters for Nashville, Tennessee, on 7-8 January 1973. Period during which freezing precipitation fell at the station is indicated by hatched lines (ZL = freezing drizzle).

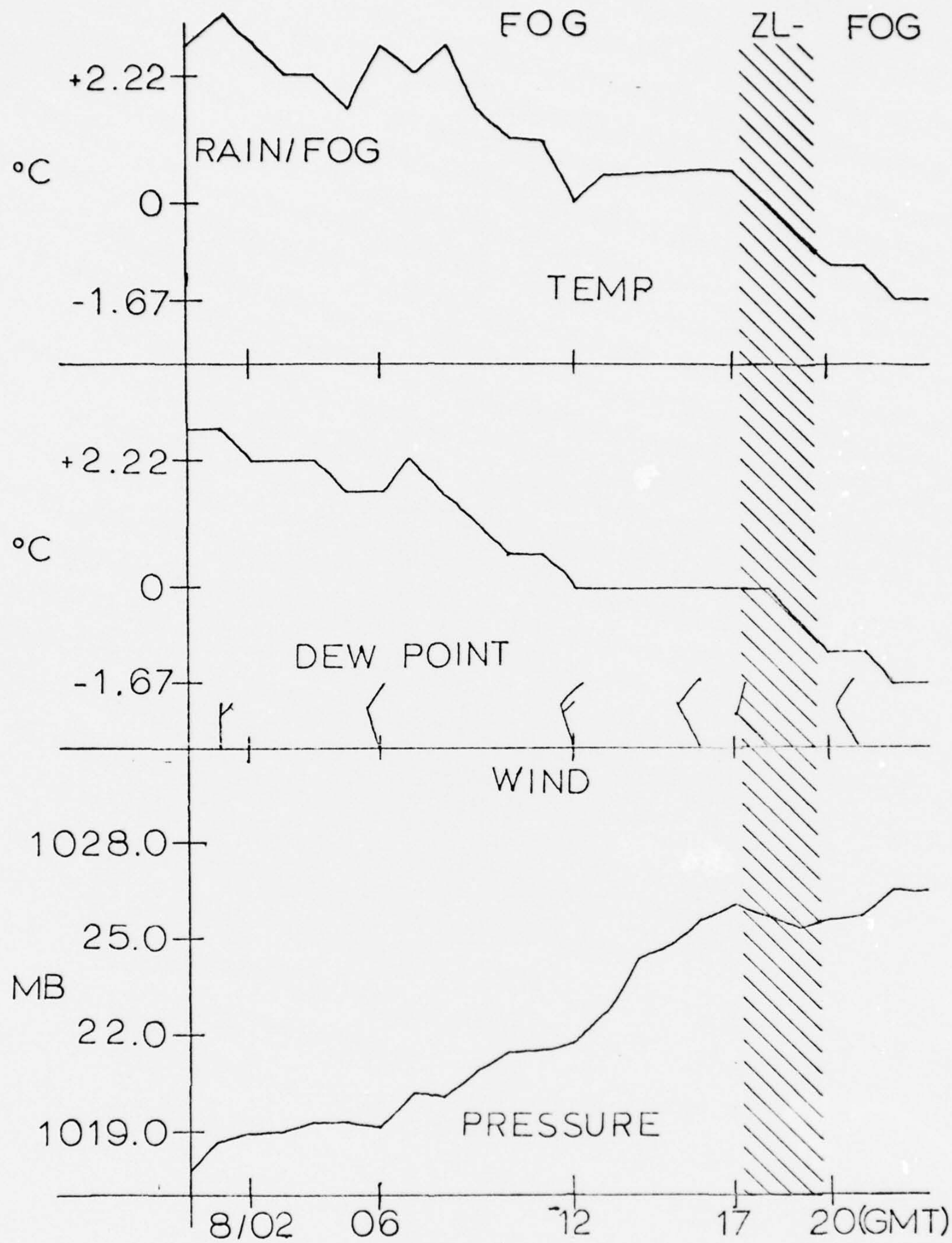

Fig. 21. Surface parameters for Jackson, Mississippi, on 8 January 1973. Period during which freezing precipitation fell at the station is indicated by hatched lines (ZL = freezing drizzle).

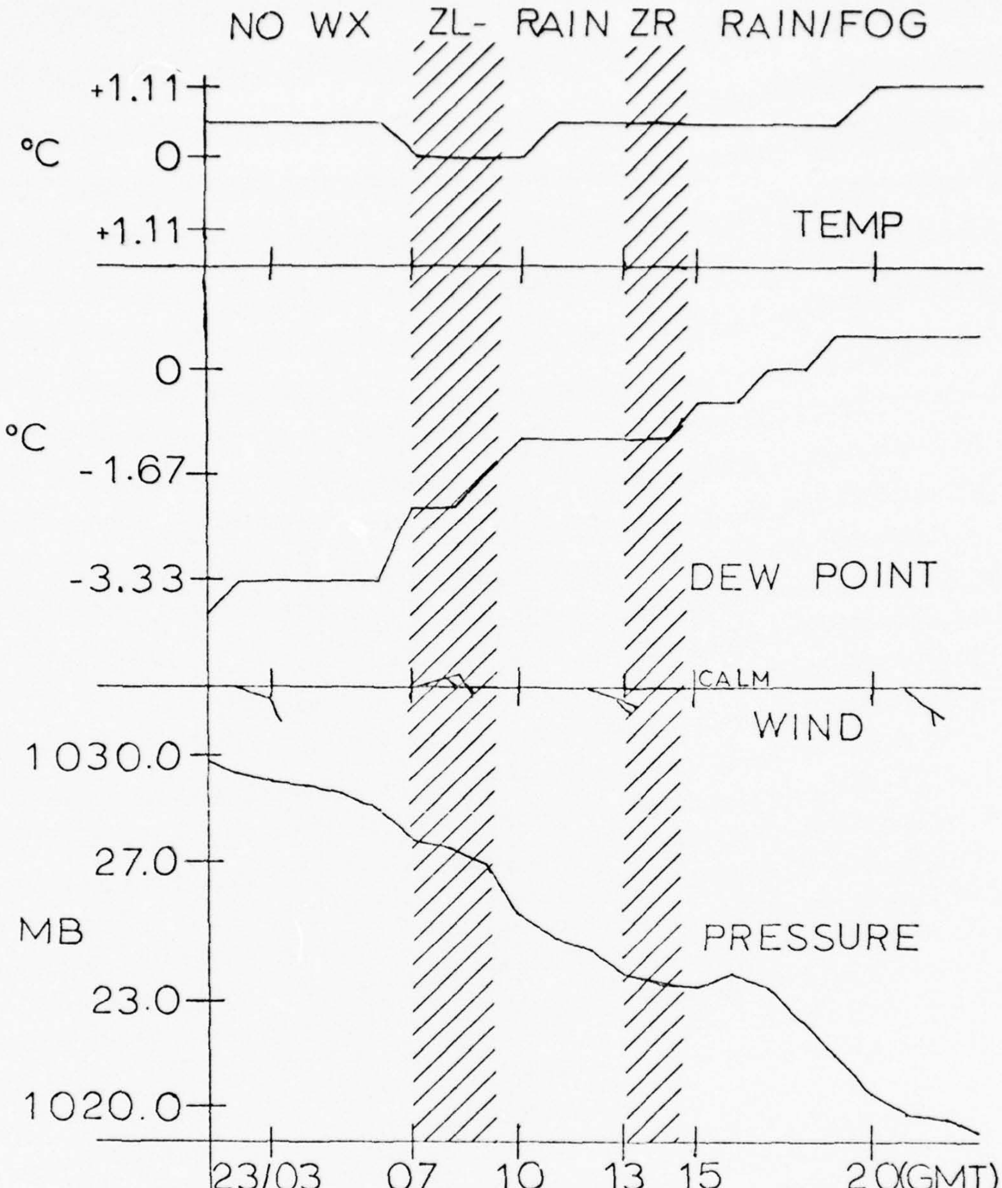

Fig. 22. Surface parameters for Little Rock, Arkansas, on 23 January 1977. Periods during which freezing precipitation fell are indicated by hatched lines (ZL = freezing drizzle, ZR = freezing rain).

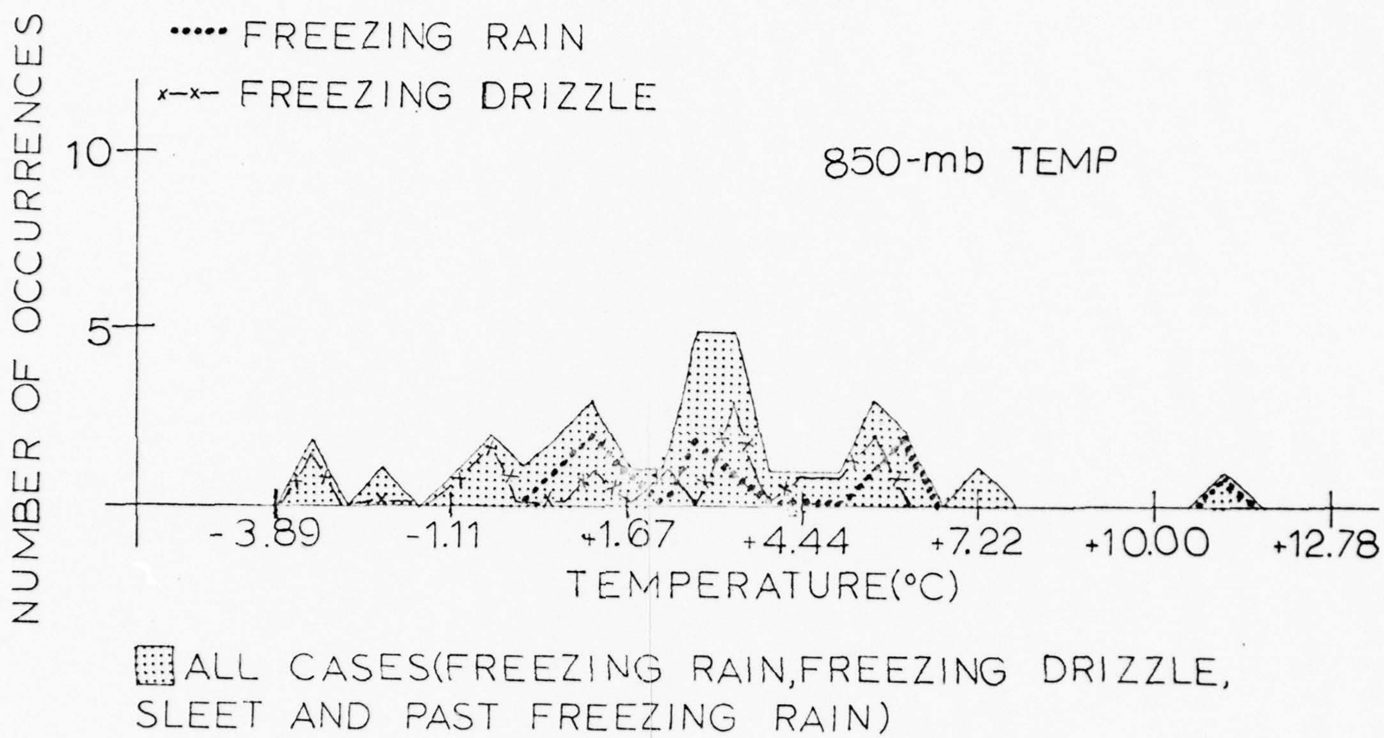

Fig. 23. The number of occurrences of freezing precipitation (various forms) over a range of 850-mb temperatures (°C). Study originally accomplished in °F. Data from selected storm cases.

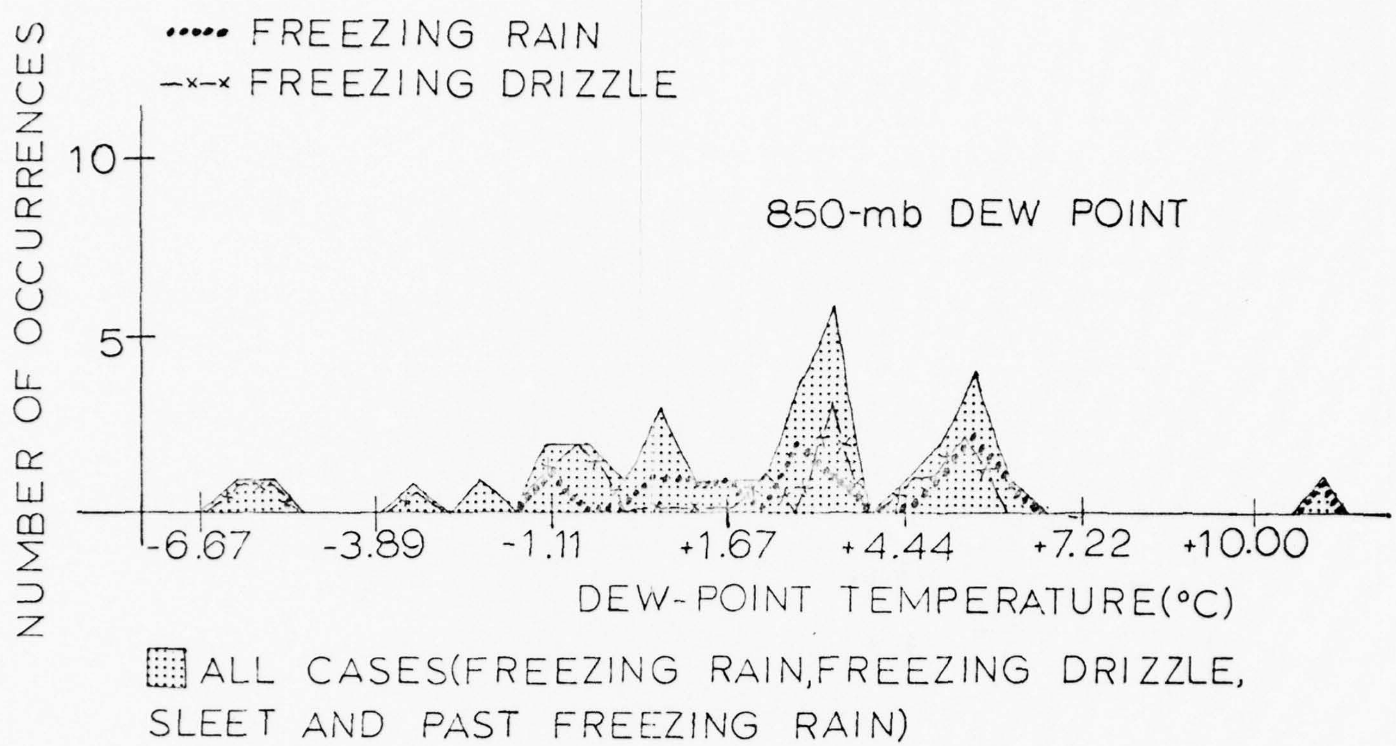

Fig. 24. The number of occurrences of freezing precipitation (various forms) over a range of 850-mb dew points (°C). Study originally accomplished in °F. Data from selected storm cases.

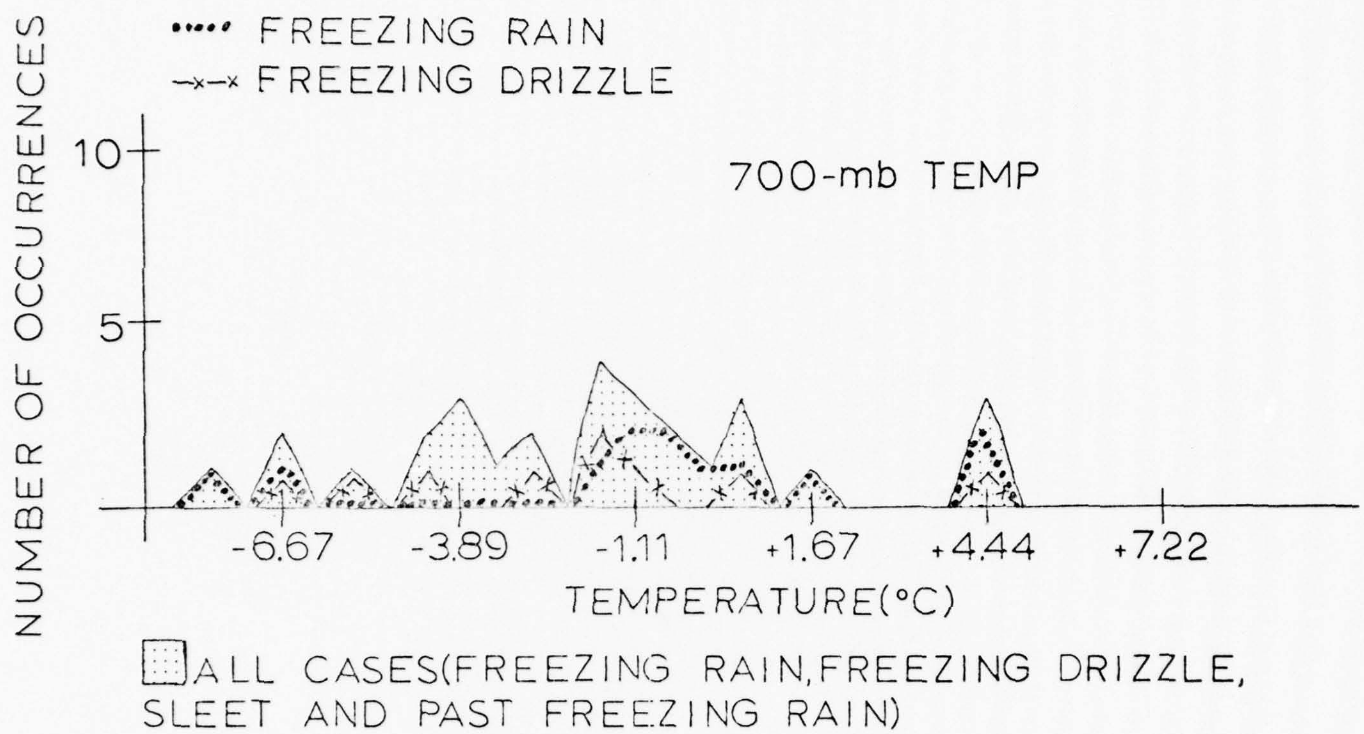

Fig. 25. The number of occurrences of freezing precipitation (various forms) over a range of 700-mb temperatures (°C). Study originally accomplished in °F. Data from selected storm cases.

the warm air sometimes extends this high, that is not always the case. This would tend to support use of the 850-mb temperature as a more convenient level at which to measure the warm air (a study of all the soundings available showed the average height of the warm air to be between these two levels). Mean, mode, and median values are once again presented in Table 2 (p. 55).

3. 850-mb and 850-mb/700-mb average winds

At the beginning of this study, it was felt strongly that the best upper-level wind to study would be that at the 850-mb level. This was because it was high enough to be above surface frictional effects and yet not too high to be above the effects of the ice storm. Results (as depicted in Fig. 26) were not disappointing, as they showed a definite tendency towards SSW to W winds. It should be noted that the trend is much the same when all forms of precipitation are plotted. However, the mean value for the cases of freezing rain was some 12-13 deg more southerly than either the mean value for all forms of freezing precipitation or the mean value for freezing drizzle cases. One disappointing aspect was the wide range of values over which freezing precipitation did occur.

To narrow the range of wind directions, the 850-mb/700-mb wind directions were averaged. Results of this parameter are shown in Fig. 27. Of particular note here is the result that the range was limited for all cases and quite distinctly with regard to freezing rain (9 of 10 cases fell between 200 and 270 deg).

Values of the mean, mode, and median for both parameters are presented in Table 2 (p. 55). Note that the mean direction of the

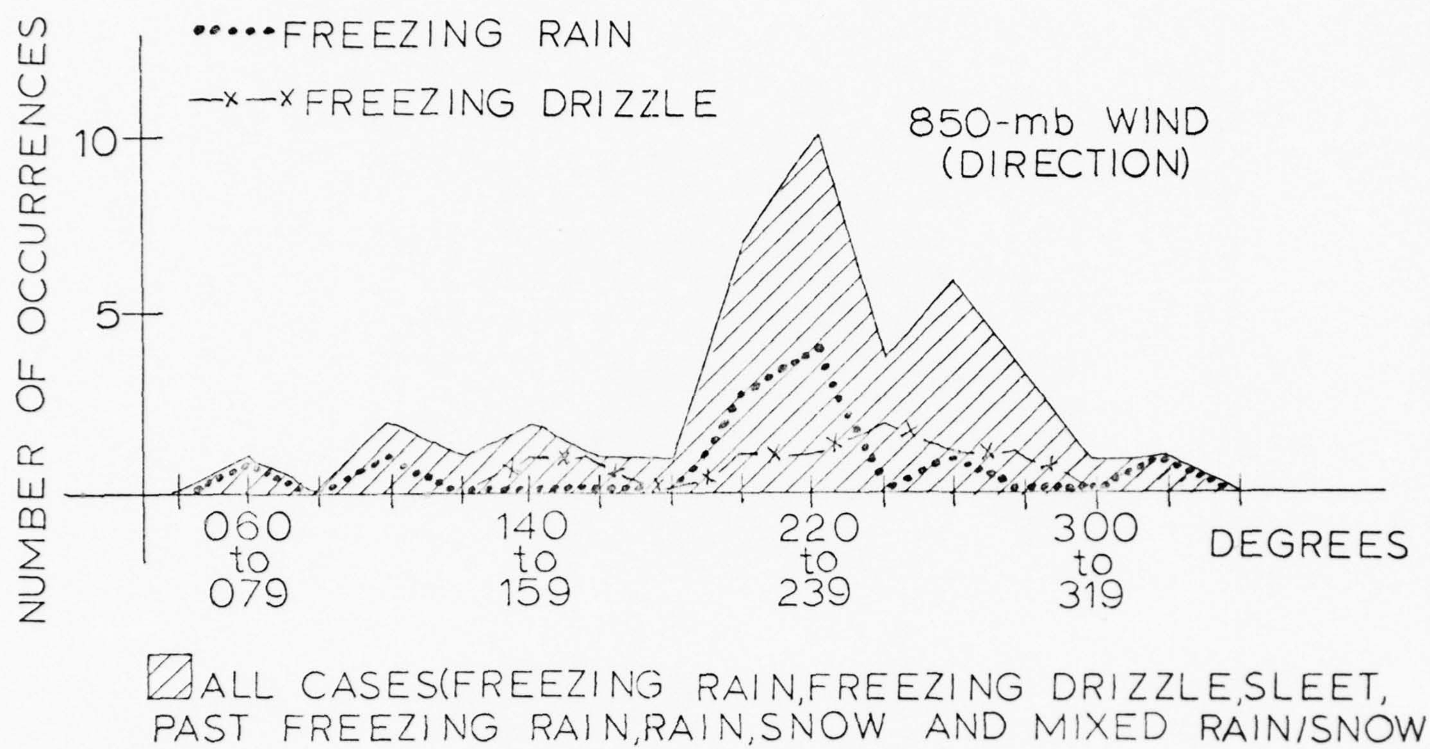

Fig. 26. The number of occurrences of precipitation (forms of freezing precipitation indicated separately) for 20-degree intervals of 850-mb wind direction. Data from selected storm cases.

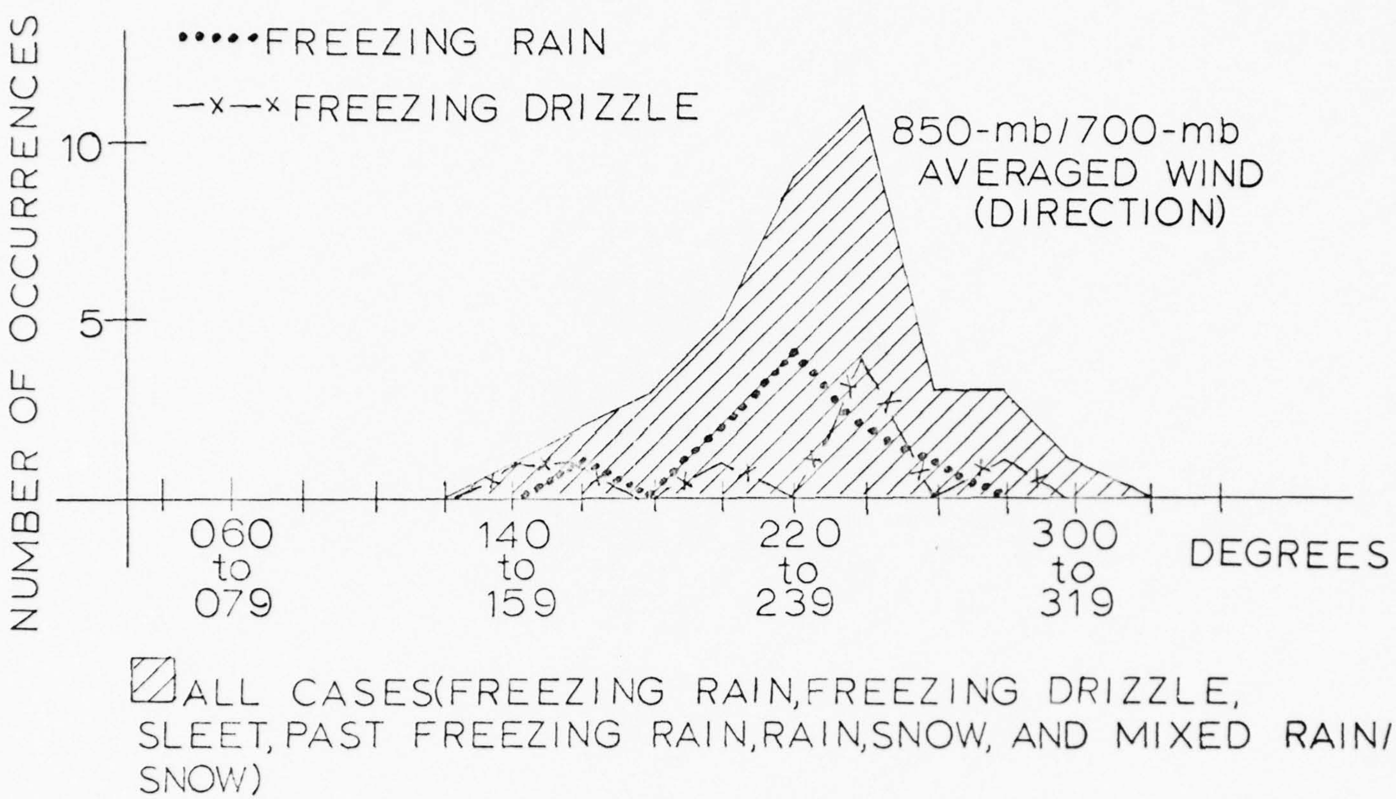

Fig. 27. The number of occurrences of precipitation (forms of freezing precipitation indicated separately) for 20-degree intervals of the averaged 850-mb and 700-mb wind directions. Data from selected storm cases.

850-mb wind for freezing drizzle was roughly 16 deg more westerly than was the mean direction for freezing rain and that the 850-mb/700-mb winds (mean values) for both forms of freezing precipitation are virtually the same (approximately 228 deg), thus indicating that there is more warm air advection aloft associated with an average sounding in freezing rain than with one in freezing drizzle.

4. Other levels

Other levels besides the surface, 850-mb, and 700-mb were considered but only briefly because of their lack of easy accessability to the forecaster (or as with the case of 500-mb, which was too high to be of any consideration for freezing precipitation occurrence). The average depth of the cold air mass is very shallow, but the surface temperature usually is not the coldest temperature within the cold air wedge. The average height of the coldest air generally was found to be about 300 to 450 m above the surface. The average level of the warm air was as noted about 2000 to 2500 m above the surface (between the 850-mb/700-mb levels). Since no charts are readily available for the 800-mb or 950-mb levels to aid the forecaster, further study in this direction was discontinued.

5. 1000-500 mb thickness

This parameter has been used as an index for rain vs snow occurrence in many studies. Tang (1974) included it as one of his parameters in delineating between snow, freezing precipitation, and rain. The critical value he found was 5460 m for freezing precipita-

tion (in combination with 850-mb temperature and surface temperature within set limits). Figure 28 shows a graph of thickness values vs number of occurrences. The two occurrences of freezing rain in excess of 5460 m were both at Little Rock, Arkansas, on successive soundings (5503 m and 5505 m). The majority of the cases of freezing precipitation (and especially freezing rain) occurred between 5330 and 5435 m. Table 2 (p. 55) presents all the appropriate mean, modal, and median values.

D. Combinations of parameters

1. Area of warm sector vs area of cold sector

Generally, in order for freezing precipitation to result, there must be a warm (above 0 °C) layer aloft and a wedge of cold (below 0 °C) air near the surface. Therefore, it was felt that it would be beneficial to compare in some fashion the relative size of the warm and cold sectors and, perhaps, to find a ratio at which they occur, or at least the relative limits of their size. The procedure was to count the parallelograms formed by the equal pressure and equal temperature lines on a skew T, Log P diagram within a sector bounded by the 0 °C isotherm and the sounding. The results were then plotted as depicted in Fig. 29. As can be seen, any relationship between the two is not clear. There do, however, appear to be fairly good limits on the size of the cold sector (all but one case between four and 32 parallelograms) and a lower boundary for the size of the warm sector (approximately 15 parallelograms) in regard to the occurrence of freezing rain or freezing drizzle.

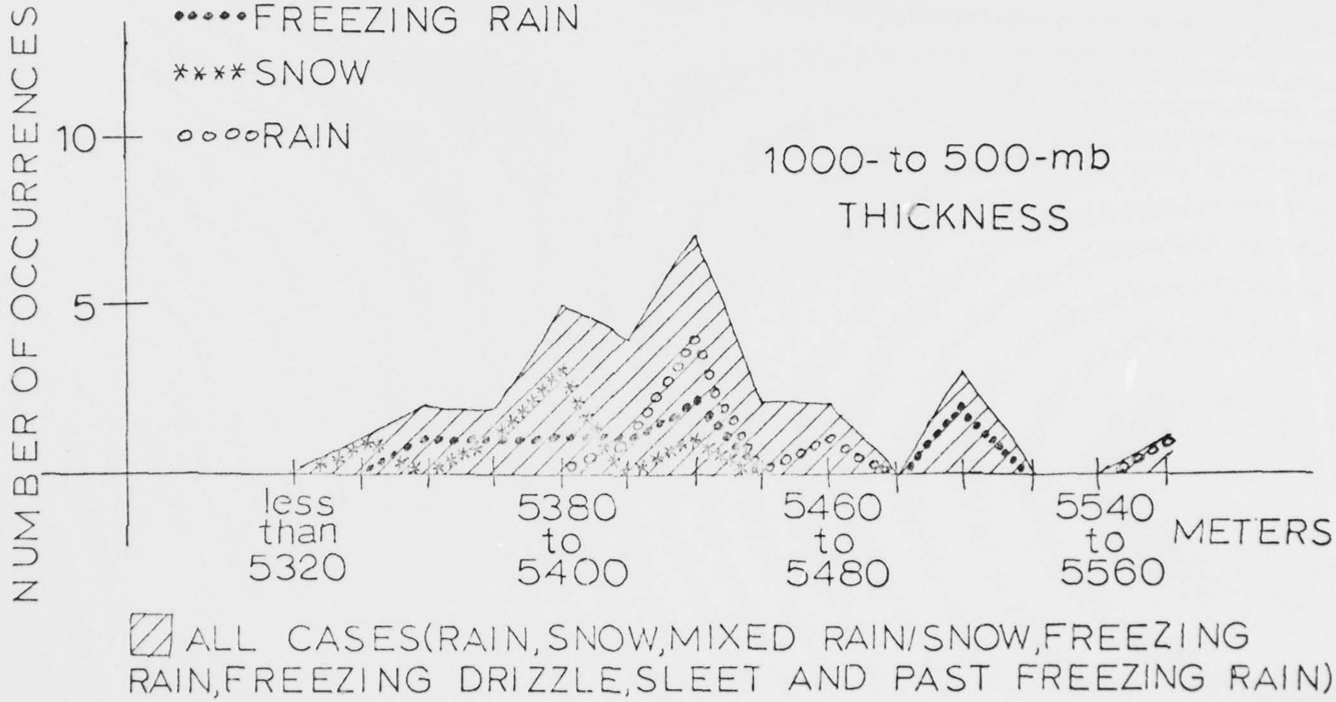

Fig. 28. The number of occurrences of precipitation (freezing rain, rain, and snow separately) for 20-meter intervals of 1000-500 mb thickness. Data from selected storm cases.

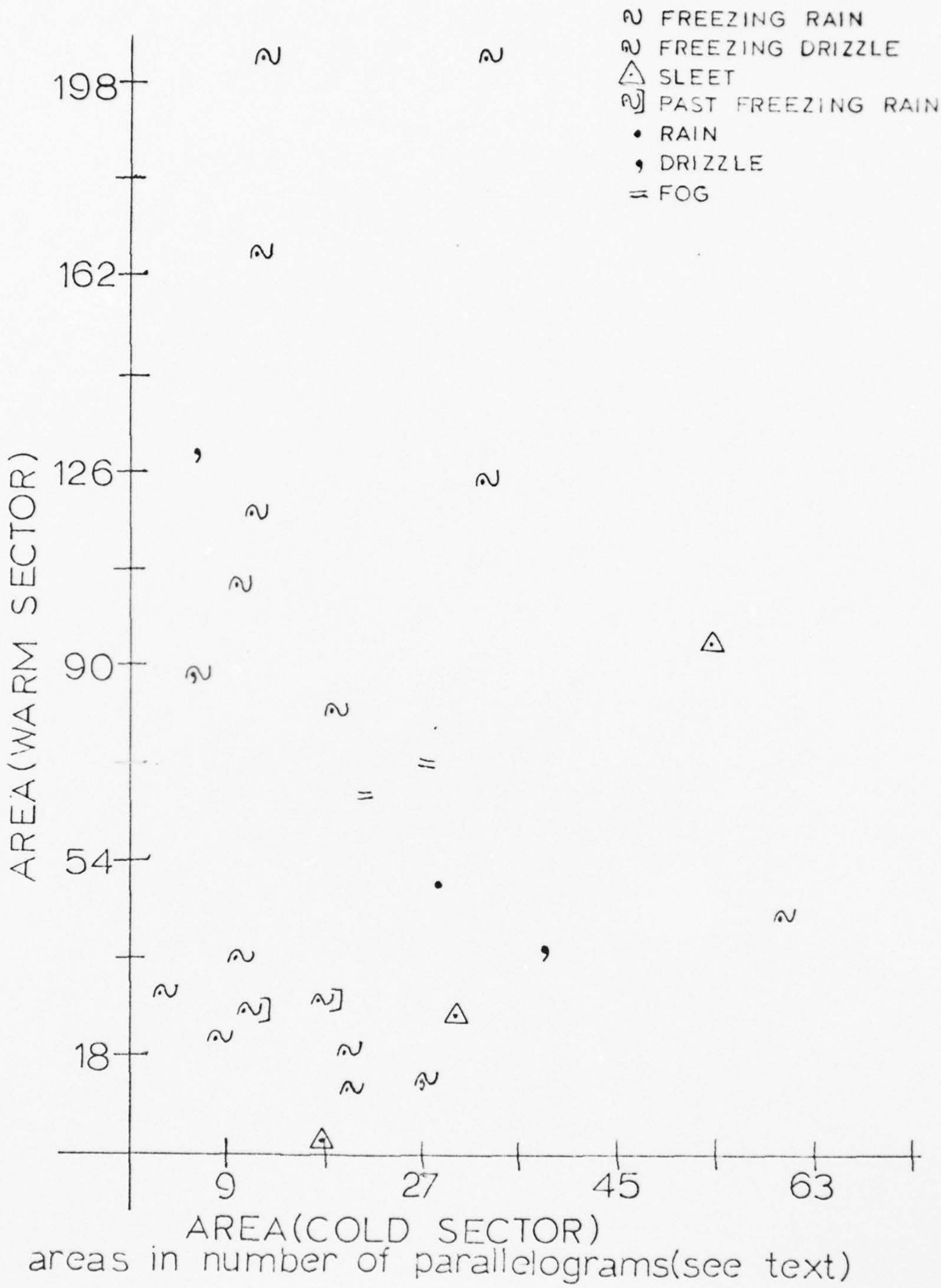

Fig. 29. Area of warm sector vs area of cold sector (within lowest 700-mb) for soundings from four selected storm cases.

2. <u>Top of cold air vs top of warm air (0°C crossings)</u>

Along the same line of reasoning as the study of relative sizes of warm and cold air sectors, there also must exist two crossings (intersections) of the 0°C isotherm by the vertical temperature plot for cases of freezing precipitation. The lower of these two could be labeled conveniently as the top of the cold air and the upper one as the top of the warm air. It was felt once again that by plotting these two parameters, one against the other, that a ratio or set of limits might be defined. Figure 30 shows such a plot. As can be seen, the top of the warmer air varies while the top of the cold air is fairly limited to between 300 and 1200 m with a mean of approximately 550 m. A lower limit for the top of the warmer air could be set at 1800 m from this sample.

3. <u>Absolute coldest vs absolute warmest temperature below 700 mb</u>

Another measure of the cold vs the warm air was to take the absolute coldest temperature vs the absolute warmest temperature below 700 mb. The procedure was simply to plot one against the other to give the results shown in Fig. 31. As usual, the use of extremes is not a good practice.

4. <u>850-mb temperature vs surface temperature</u>

Because well-defined limits were found for freezing rain by using either surface temperature or 850-mb temperature, it was felt that a graph utilizing both of these parameters would delineate even better the areas of its occurrence. Figure 32 shows a plot of

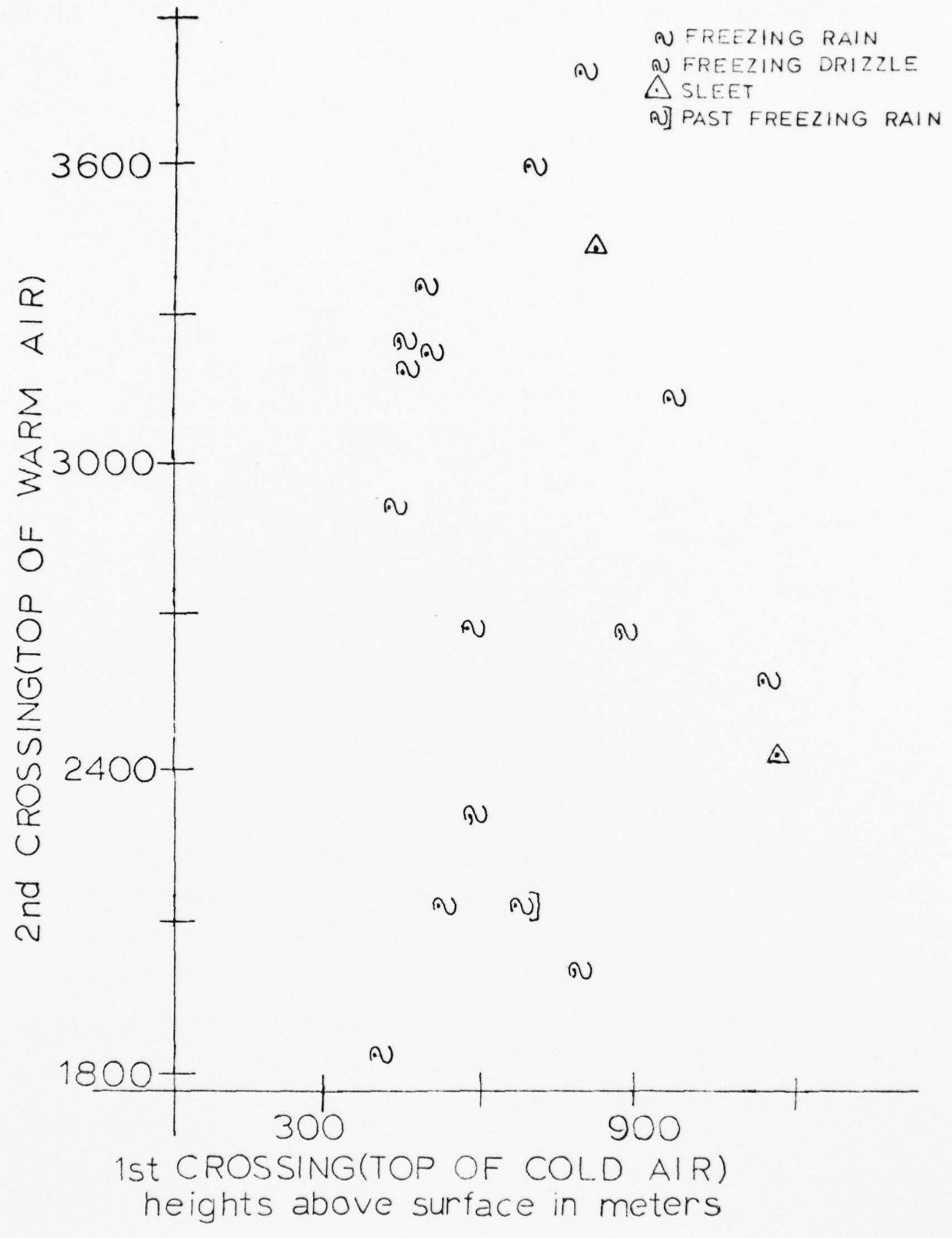

Fig. 30. Top of cold air sector (first crossing of 0°C isotherm) vs top of warm air sector (second crossing of 0°C isotherm) for soundings from four selected storm cases in meters above surface.

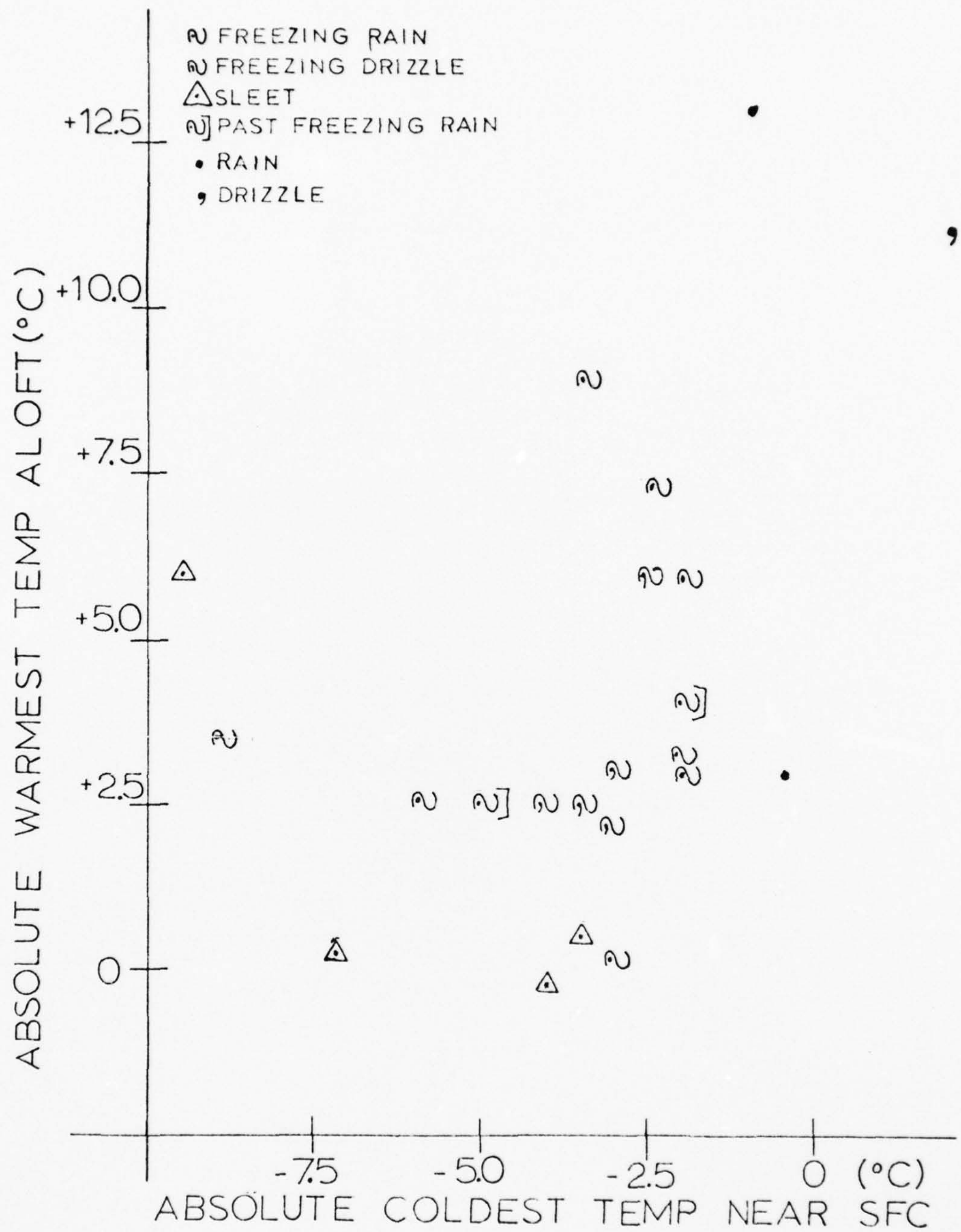

Fig. 31. Absolute coldest vs absolute warmest temperatures (°C) in lowest 700-mb for soundings from four selected storm cases.

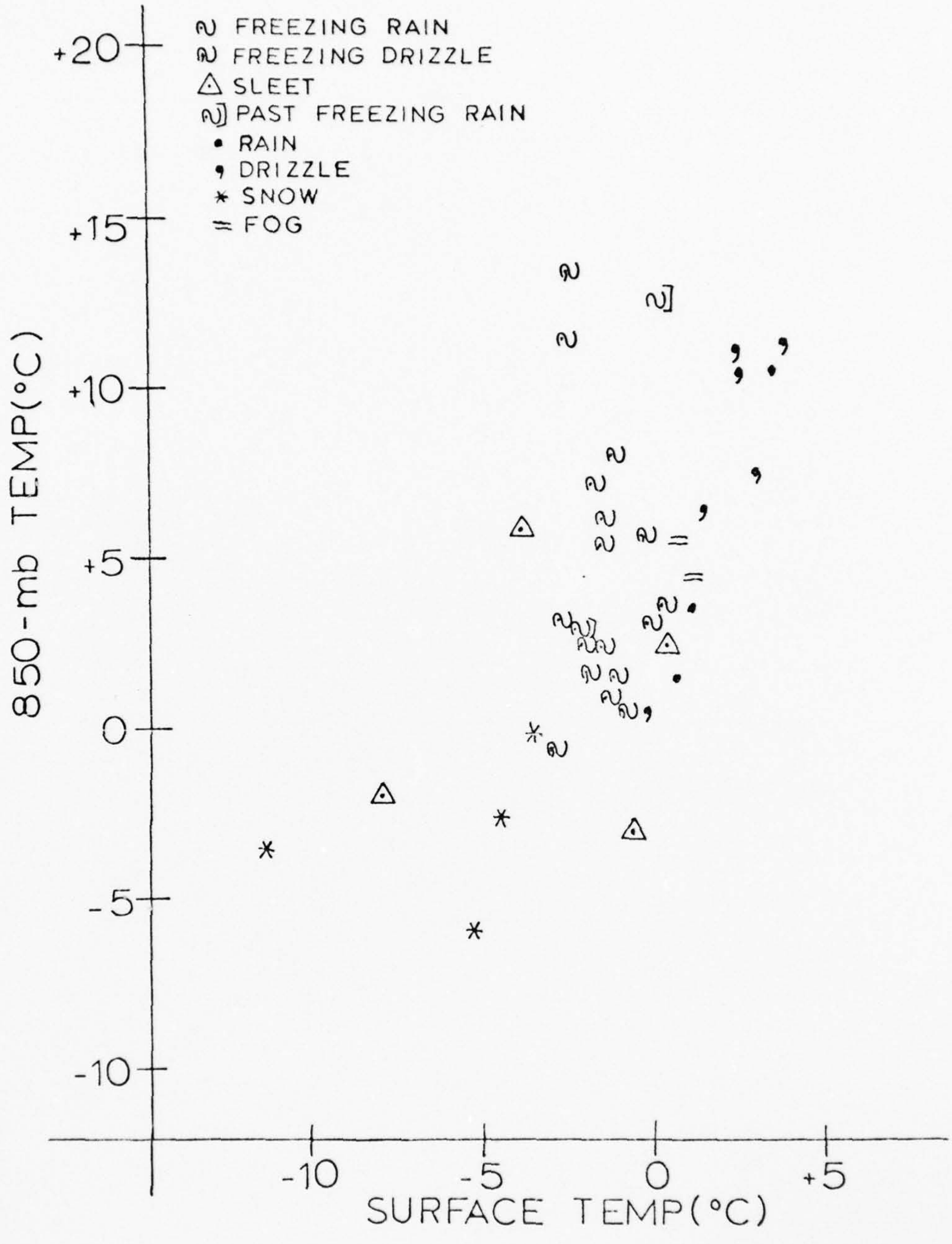

Fig. 32. Surface temperature vs 850-mb temperature (°C) for soundings from four selected storm cases.

weather types observed during the four storm cases and the relative surface and 850-mb temperatures at which they occurred. A fairly well-formed pattern of precipitation types shows signs of emerging from this plot, but conclusions will be left till later in this paper.

E. Discussion of data extremes

None of the surface observations or soundings observed were deemed so extreme as to be deleted from any of the individual parameter studies. However, there were some values which stood out from the others. In regard to surface temperature, all observed cases ranged from -5 to +1.11 °C except for one case of freezing drizzle which occurred at -7.22°C. Surface dew point ranged from -6.11 to +10.56°C except for one case of freezing drizzle at -10°C, one at -7.22°C, and one case of sleet at -12.22°C. The 850-mb temperature and dew-point values were not closely packed, but several values did stand out. A temperature of +11.11°C occurred with one case of freezing rain, and dew points of -6.11, -5.56 (with freezing drizzle), and +11.11°C with freezing rain occurred.

The most extreme case with respect to the 850-mb wind directions observed (for all precipitation forms) was 070 degrees, which occurred on a Little Rock, Arkansas, sounding at a time when freezing rain was occurring at the surface. Thickness values of note above 5460 m for which freezing precipitation fell included the two already noted at Little Rock (freezing rain) and one each at Ft. Worth (freezing drizzle) with a value of 5517 m and Nashville (freezing drizzle) with a value of 5465 m.

F. Generalizations on selected storms

Although the sample size was small, certain generalizations can be made from the above results. First, in regard to the obvious, freezing rain occurred generally with surface temperatures only a degree or two below 0°C, 850-mb temperatures 3-4 deg above 0°C, and 700-mb temp around 0°C. In the mean, freezing drizzle occurred at generally colder temperatures (at all three levels) but this difference was most apparent at 850 mb where it was more than 2°C. Occurrences of freezing rain tended to occur when winds were between 220 and 239 deg for both the 850-mb wind and the 850-mb/700-mb averaged wind. For freezing drizzle, the wind directions were some 20 deg more westerly (although the mean values for the 850-mb/700-mb averaged wind for freezing rain and freezing drizzle were similar). The data also indicated that sleet required, on the average, a colder sounding (at the surface, 850 mb and 700 mb) than either freezing rain or freezing drizzle.

V. ANALYSIS OF PARAMETERS FROM TOTAL SAMPLE

A. Stratification of data in regard to area and weather type

As mentioned previously, the soundings compiled for this study include an area larger than the selected study area. So as to enlarge the sample size and thus lend further credence to any conclusions reached. A stratification of the number of soundings from each particular station is given in Table 3 (the stations with an asterisk next to them are within the study area). Also indicated are the number of soundings each reporting surface observations of: mixed snow and rain, freezing rain, freezing drizzle, past freezing rain, and sleet for each station. Weather types are as defined by AWSM 105-22, "Local Weather Analysis Program," U.S. Air Force, Air Weather Service (MAC), Scott AFB, Illinois, 2 January 1969 and Code table 4 of the Federal Meteorological Handbook No. 2, Synoptic Code published jointly by the U.S. Department of Commerce, U.S. Department of Defense and the U.S. Department of Transportation, 1 January 1969. Of 215 total soundings, 76 were from the study area (35.35%) as were 33 out of 108 reports of freezing precipitation (30.56%). The sample is derived from 43 different radiosonde stations.

Table 4 shows a further stratification of the soundings plotted in regards to synoptic designator and weather type. Many of the rain and snow soundings plotted reported a change from either rain to snow or snow to rain within the past couple of hours. All of the soundings are between late December and the end of February for the years of 1968 through 1977, inclusive. They reflect winter weather

Table 3. Stratification of soundings.

Station	Total Number Used	Mixed Snow/Rain	Freezing Rain	Freezing Drizzle	Sleet	Past Freezing Rain
* LIT	14	0	5	1	2	2
* BNA	16	0	2	3	0	0
* SHV	8	0	3	0	0	1
* GSW(or FTW)	14	0	1	4	0	1
HTS	6	1	2	0	0	0
SLO	7	0	3	0	0	1
ABQ	1	0	0	0	0	0
PHL	2	0	2	0	0	0
PIA	9	0	2	1	0	0
UMN	18	1	4	4	0	0
BUF	8	2	1	1	1	1
SLC	2	0	0	0	0	0
MAF	6	0	2	3	0	1
DDC	7	0	0	2	0	0
FNT	6	0	0	3	1	0
OMA	2	0	0	1	0	0
TOP	9	0	0	3	2	0
GJT	1	0	0	0	0	0
* AHN	5	0	2	0	2	0
GSO	4	0	0	0	2	0
DRT	1	0	0	1	0	0
DAY	8	0	1	3	1	0
PIT	8	0	1	1	1	1
AMA	5	0	0	4	0	1
IAD(DCA)	4	0	3	1	0	0
GRB	2	0	0	0	0	0
TIK(OKC)	6	0	0	3	0	0
BOI	1	0	0	0	0	0
ABI	2	0	1	1	0	0
UIL	2	0	0	1	0	0
* JAN	9	0	1	0	1	1
* MGM	3	0	0	0	0	0
* LCH	3	0	1	0	0	0
ALB	4	0	2	1	1	0
CHS	4	0	1	1	0	0
* AYS	1	0	0	0	0	0
* BVE	2	0	0	0	0	0
TPA	1	0	0	0	0	0
RAP	1	0	0	0	0	0
GGG	1	0	0	0	0	0

Table 3. (Continued)

Station	Total Number Used	Mixed Snow/Rain	Freezing Rain	Freezing Drizzle	Sleet	Past Freezing Rain
BRO	1	0	0	1	0	0
* VCT	1	0	0	0	0	0
HAT	1	0	0	0	0	0
Totals	215	4	40	44	14	10

*Asterisk indicates stations within study area.

Table 4. Total plotted soundings by weather types.

Weather	Synoptic designator	Number of soundings used
No weather	01, 02, 03	21
Ground fog	10	4
Past rain	21	1
Past snow	22	1
Past mixed rain/snow	23	1
Past freezing rain	24	10
Past rainshower	25	1
Past snowshower	26	1
Past thunderstorm	29	1
Fog	47	4
Drizzle	50, 51, 53	13
Freezing drizzle	56	44
Rain	60, 61, 63	22
Freezing rain	66	40
Mixed rain/snow	68	4
Snow	70, 71, 75	26
Ice needles	76	2
Granular snow	77	3
Snow crystals	78	1
Sleet	79	14
Thunderstorm	95	1
		215

types in or around areas of freezing precipitation as located through climatic records. Figures 33, 34, 35, and 36 show representative soundings of freezing rain, freezing drizzle, and sleet as well as an unusual case of freezing drizzle, with no temperature above 0° C at any level.

B. Surface parameters

1. Temperature

Surface temperature was found to be an effective parameter in narrowing down potential areas of freezing precipitation. Bryson and Hare's (1974) range of 0°C to -5°C proved to be fairly accurate particularly in regard to freezing rain, since several cases of freezing drizzle occurred with surface temperatures between -5 and -10°C. Figure 37 shows graphs of temperature vs number of occurrences for the precipitation forms indicated. Table 5 lists the applicable mean, mode, and median values. One important feature to note is the nearly 1.4°C difference between the mean temperature for freezing rain and freezing drizzle. Also notice that more than half of the occurrences of freezing rain are with a surface temperature within 1.5° of 0°C, whereas the majority of freezing drizzle occurrences are 3-5°C below zero. Finally note the difference in modes between freezing rain and freezing drizzle (nearly 2.8°C), which also indicates more occurrences of freezing drizzle at colder surface temperatures.

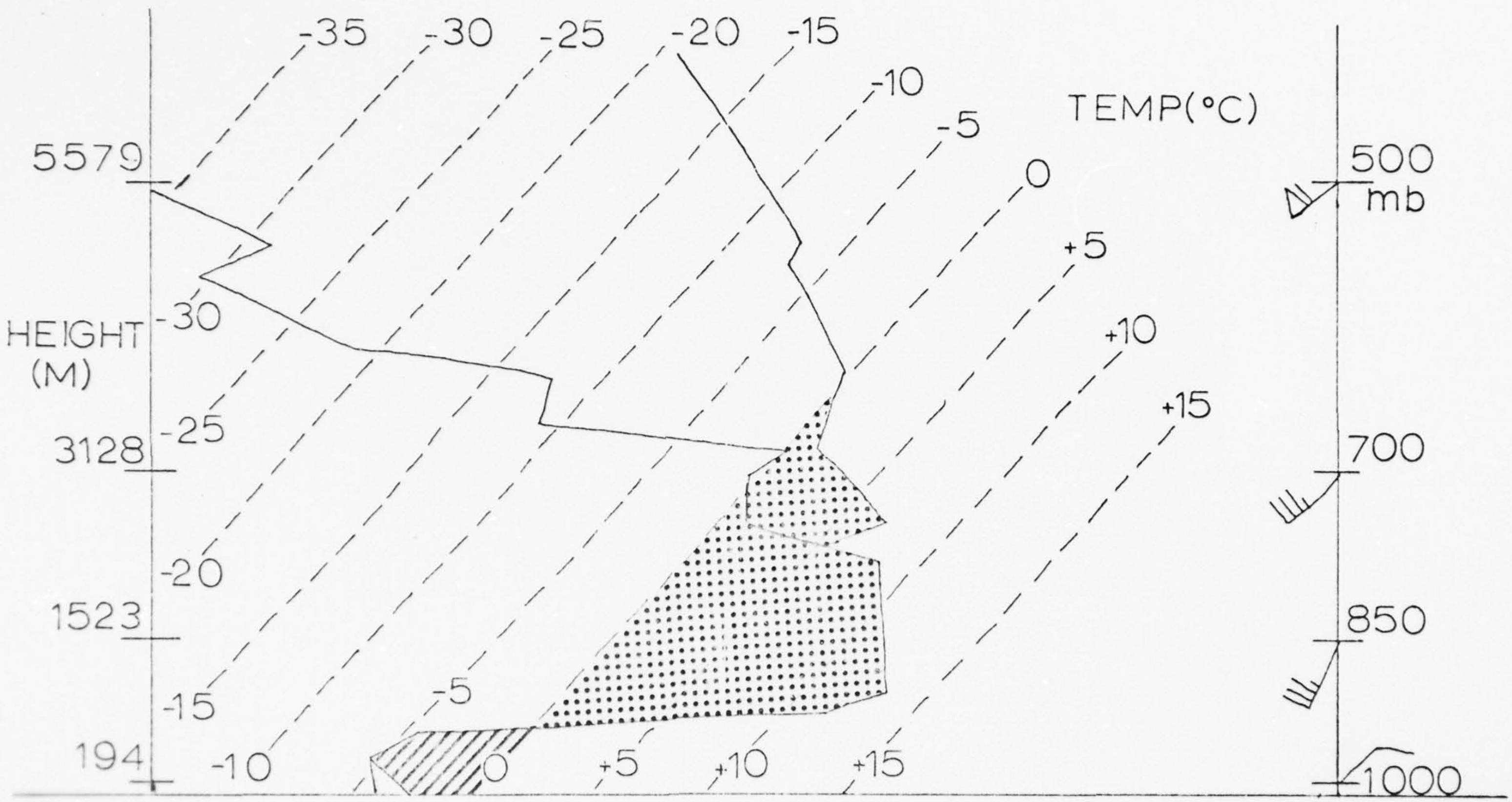

Fig. 33. Typical sounding reporting freezing rain at the surface (Little Rock, Arkansas, 12 December 1972, 0000 GMT). Warm sector (above 0°C) aloft is stippled and cold sector (below 0°C) near surface is hatched.

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FREEZING PRECIPITATION IN THE SOUTHEASTERN UNITED STATES.(U)
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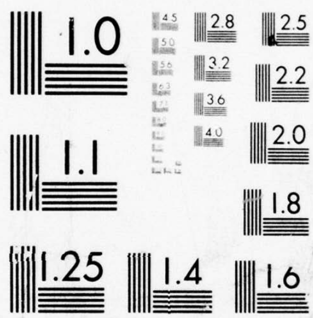

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

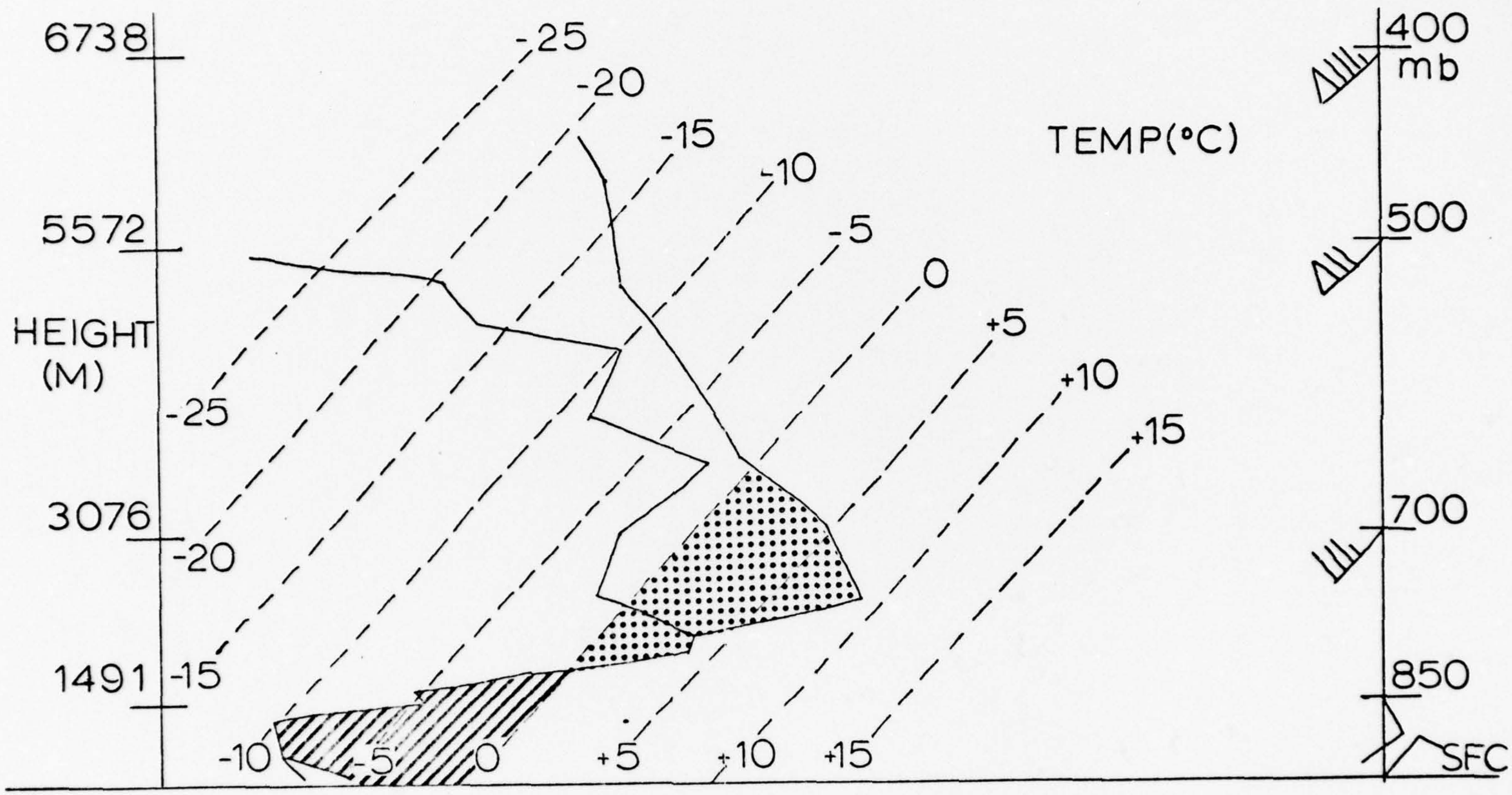

Fig. 34. Typical sounding reporting freezing drizzle at the surface (Midland, Texas, 11 December 1972, 1200 GMT). Warm sector (above 0°C) aloft is stippled and cold sector (below 0°C) near surface is hatched.

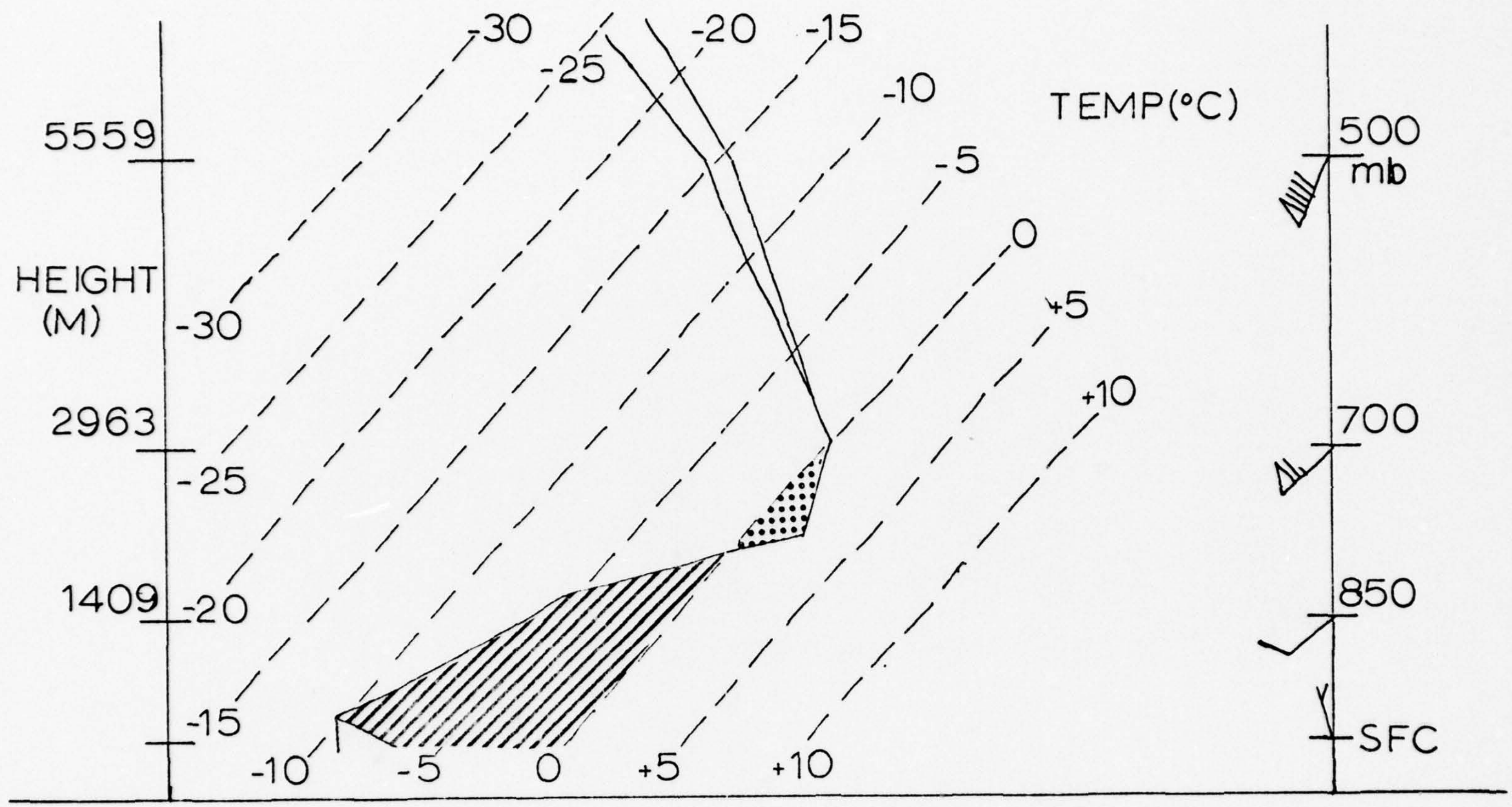

Fig. 35. Typical sounding reporting sleet at the surface (Topeka, Kansas, 12 December 1972, 1200 GMT). Warm sector (above 0°C) aloft is stippled and cold sector (below 0°C) near surface is hatched.

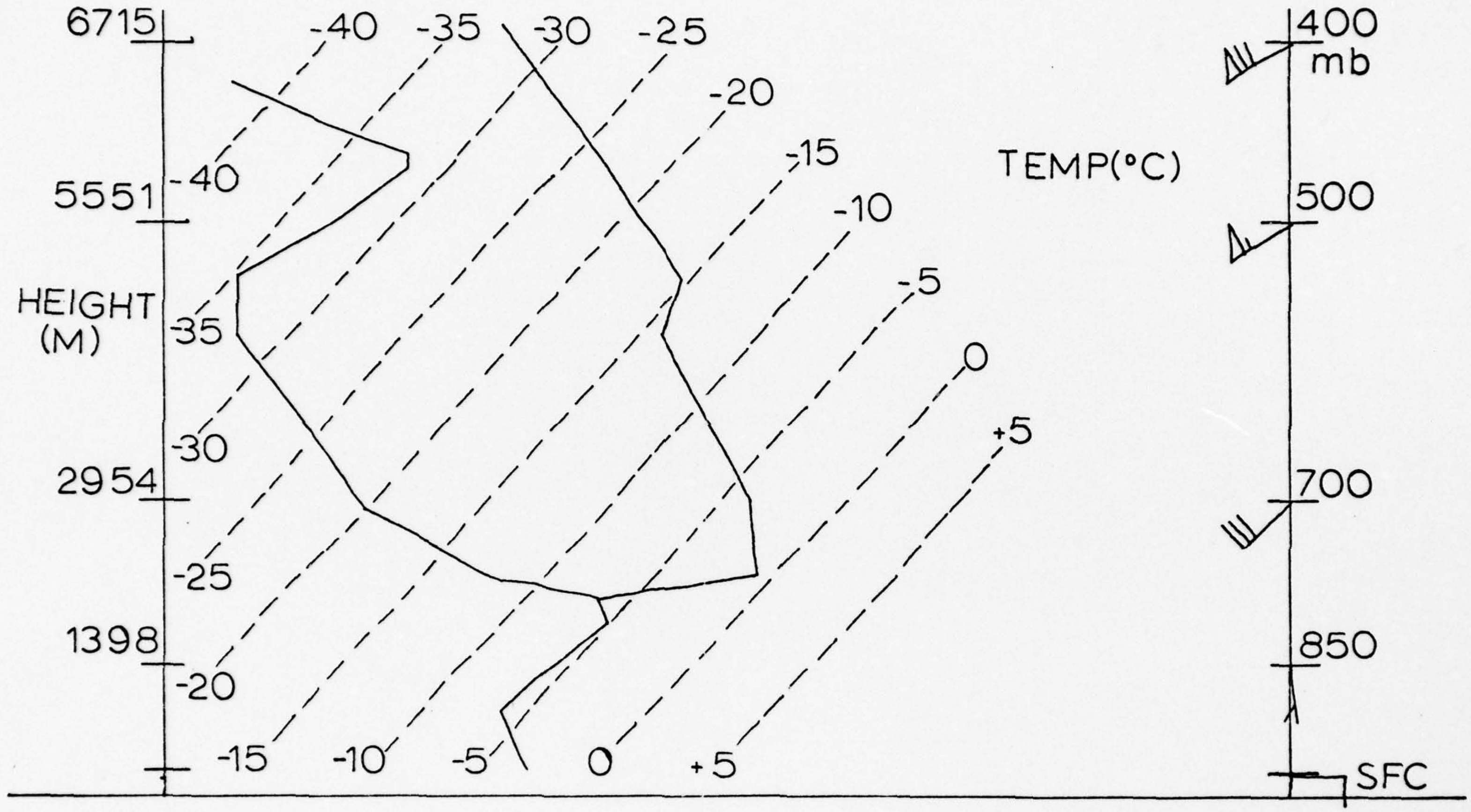

Fig. 36. Sounding reporting freezing drizzle at the surface with no warm sector (above 0°C) aloft (Omaha, Nebraska, 4 February 1971, 0000 GMT).

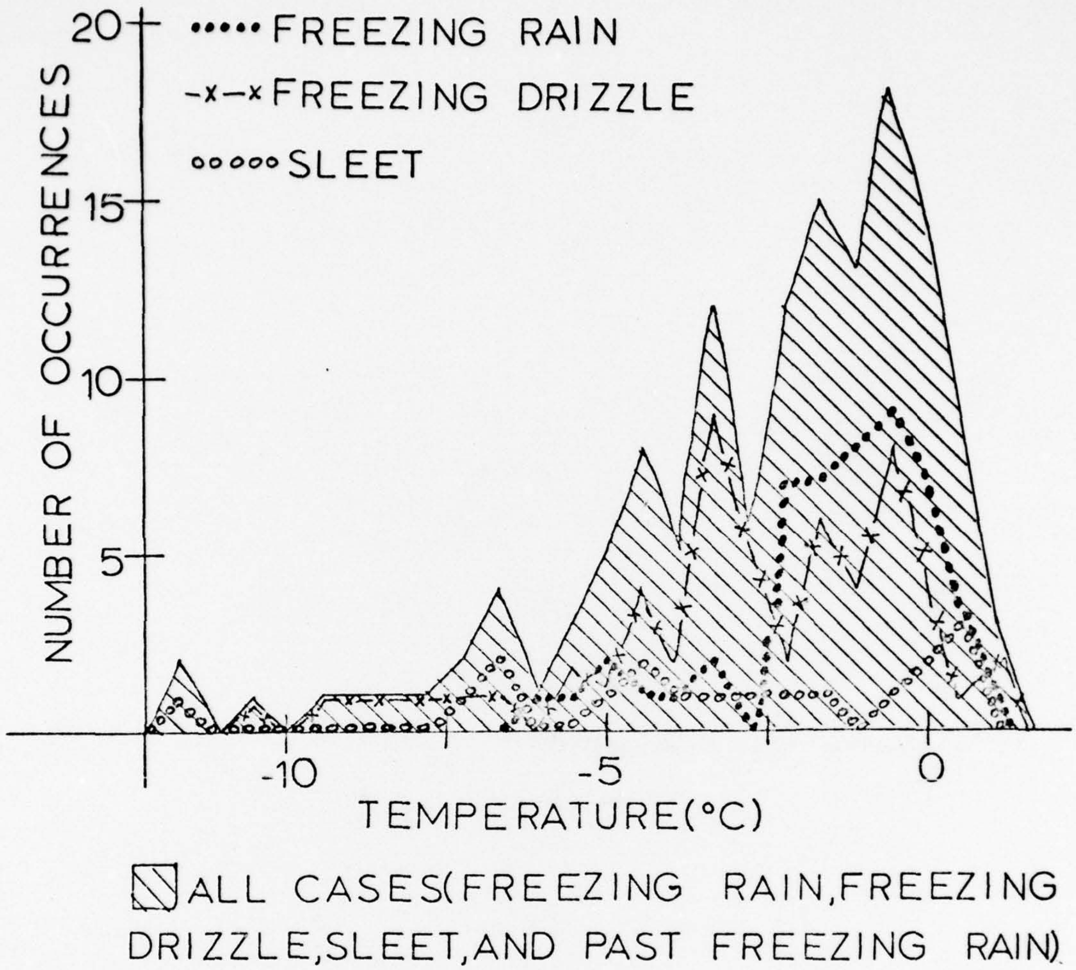

Fig. 37. The number of occurrences of freezing precipitation (various forms) over a range of surface temperatures (°C) for the total sample.

Table 5. Table of means, modes and medians for total sample (all temperatures in °C).

Parameter	Mean	Mode	Median	Number of Occurrences
Surface Temperature				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	-2.50	-0.56	-1.67	136
Freezing rain (66) alone	-1.56	-0.56	-1.11	49
Freezing drizzle (56) alone	-2.92	-3.33	-2.78	58
Sleet (79) alone	-3.27	+0.56	-3.06	18
Surface Dew Point				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	-4.09	-2.22	-3.33	136
Freezing rain (66) alone	-3.18	-2.22	-2.78	49
Freezing drizzle (56) alone	-4.22	-1.67	-3.89	58
Sleet (79) alone	-5.68	-1.11	-5.56	18
850-mb Temperature				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	+1.78	+3.33	+2.22	108
Freezing rain (66) alone	+4.25	+3.33	+3.61	40
Freezing drizzle (56) alone	+0.56	-----	+0.56	43
Sleet (79) alone	-0.30	-----	0	13
850-mb Dew Point				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	+1.56	+3.06	+2.22	108
Freezing rain (66) alone	+4.07	+5.00	+3.61	40
Freezing drizzle (56) alone	+0.08	-----	0	43
Sleet (79) alone	-0.47	-----	0	13

Table 5. (Continued)

Parameter	Mean	Mode	Median	Number of Occurrences
700-mb Temperature				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	-2.14	0	-1.67	104
Freezing rain (66) alone	-0.54	0	0	39
Freezing drizzle (56) alone	-2.34	-----	-2.78	42
Sleet (79) alone	-2.31	-----	-2.78	13
850-mb Wind Direction (degrees)				
All cases rain, snow, drizzle, mixed rain/snow, freezing rain, freezing drizzle, sleet and past freezing rain (61, 71, 51, 68, 66, 56, 79, 24)	212.59	230	-----	139
Cases of freezing rain, freezing drizzle and past freezing rain (66, 56, 24) alone	212.59	230	-----	81
Freezing rain (66) alone	217.89	230	-----	38
Freezing drizzle (56) alone	222.35	250	-----	34
Averaged 850-mb/700-mb Wind Direction (degrees)				
All cases rain, snow, drizzle, mixed rain/snow, freezing rain, freezing drizzle, sleet and past freezing rain (61, 71, 51, 68, 66, 56, 79, 24)	227.05	230	-----	130
Cases of freezing rain, freezing drizzle and past freezing rain (66, 56, 24) alone	229.20	230	-----	75
Freezing rain (66) alone	226.88	230	-----	32
Freezing drizzle (56) alone	234.12	250	-----	34
1000-500 mb Thickness (m)				
Cases of freezing rain, freezing drizzle, sleet and past freezing rain (66, 56, 79, 24)	5395.87	-----	5390	62
Freezing rain (66) alone	4393.45	-----	5390	29

2. Dew point

Surface dew point showed much the same variability as did surface temperature although the range is not as conveniently narrow. Figure 38 shows graphs of dew-point temperature vs number of occurrences. Note the distinct peak of the freezing rain curve at -2.22° C, while freezing drizzle has two main peaks at -1.67° C and -4.44° C. Also noteworthy is the more than one full degree difference between the mean values for freezing rain, freezing drizzle, and sleet. Table 5 presents the mean, mode, and median values for this parameter.

3. Wind, pressure, and visibility

These parameters, as was mentioned in chapter 4, did not show any trends with regard to the sample as a whole. It was mentioned that on an individual station-to-station basis, they could prove useful (along with other parameters) in deriving a polished forecast.

C. Upper-air parameters

1. 850-mb temperature and dew point

Figure 39 shows a graph of 850-mb temperatures vs number of occurrences. As can be seen readily, the line encompassing all cases covers a wide range (actually even wider than indicated, since extreme reports of -10.56°C and +13.89°C, both from reports of freezing drizzle, could not be plotted due to lack of space available). However, if freezing rain alone were considered, the range is narrowed significantly to between -2.22 and +11.67°C (36 out of

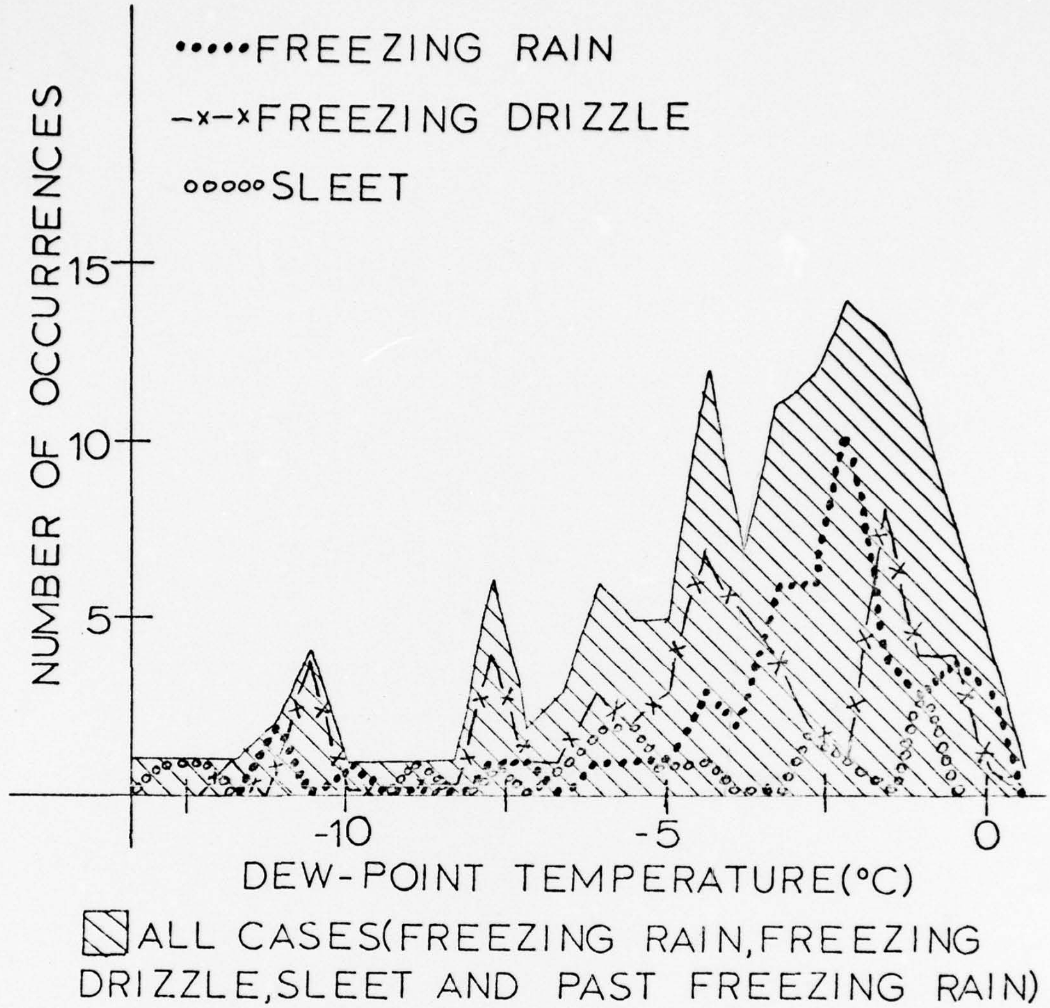

Fig. 38. The number of occurrences of freezing precipitation (various forms) over a range of surface dew points (°C) for the total sample.

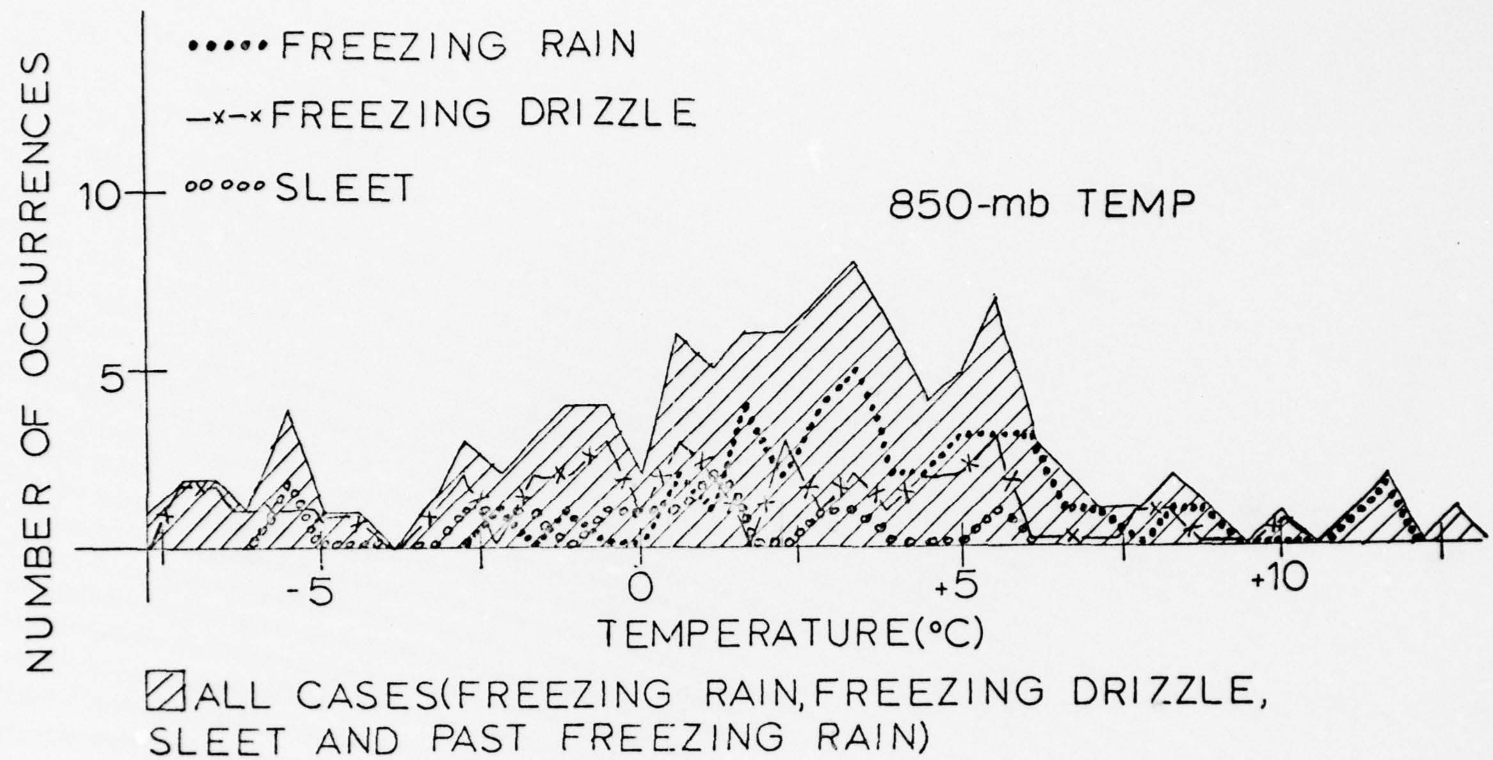

Fig. 39. The number of occurrences of freezing precipitation (various forms) over a range of 850-mb temperatures (°C) for the total sample.

40 cases between +0.56 and +8.89°C). Also note that while 38 out of 40 cases of freezing rain occurred with an 850-mb temperature above 0°C, 20 out of 43 cases of freezing drizzle had 850-mb temperatures of 0°C or less (nearly 50%). As was the case in chapter 3, there is a very distinct difference in the arithmetic means for freezing rain and freezing drizzle (about 3.7°C).

Figure 40 shows similar graphs of dew-point temperatures vs number of occurrences with very similar results except that there is no longer a distinct peak in the freezing rain curve. However, the range of the various precipitation forms are changed little. Table 5 (p. 89) shows appropriate mean, mode, and median value for both parameters.

2. <u>700-mb temperature</u>

As was noted in chapter 4, the 700-mb temperature was not as good a measure of the warm air aloft as was 850-mb temperature because the 700-mb level was sometimes above the warm air. Figure 41 (which shows graphs of 700-mb temperature vs number of occurrences) indicates this very well, as the number of observations is nearly equally divided between those above and below 0°C. The range for freezing rain is fairly clear-cut with 36 out of the 39 cases falling between -3.89 and +4.44°C. Overall range is from -12.22 to +8.33°C with both extremes being cases of freezing drizzle. Table 5 (p. 89) once again shows relevant value of mean, mode and median.

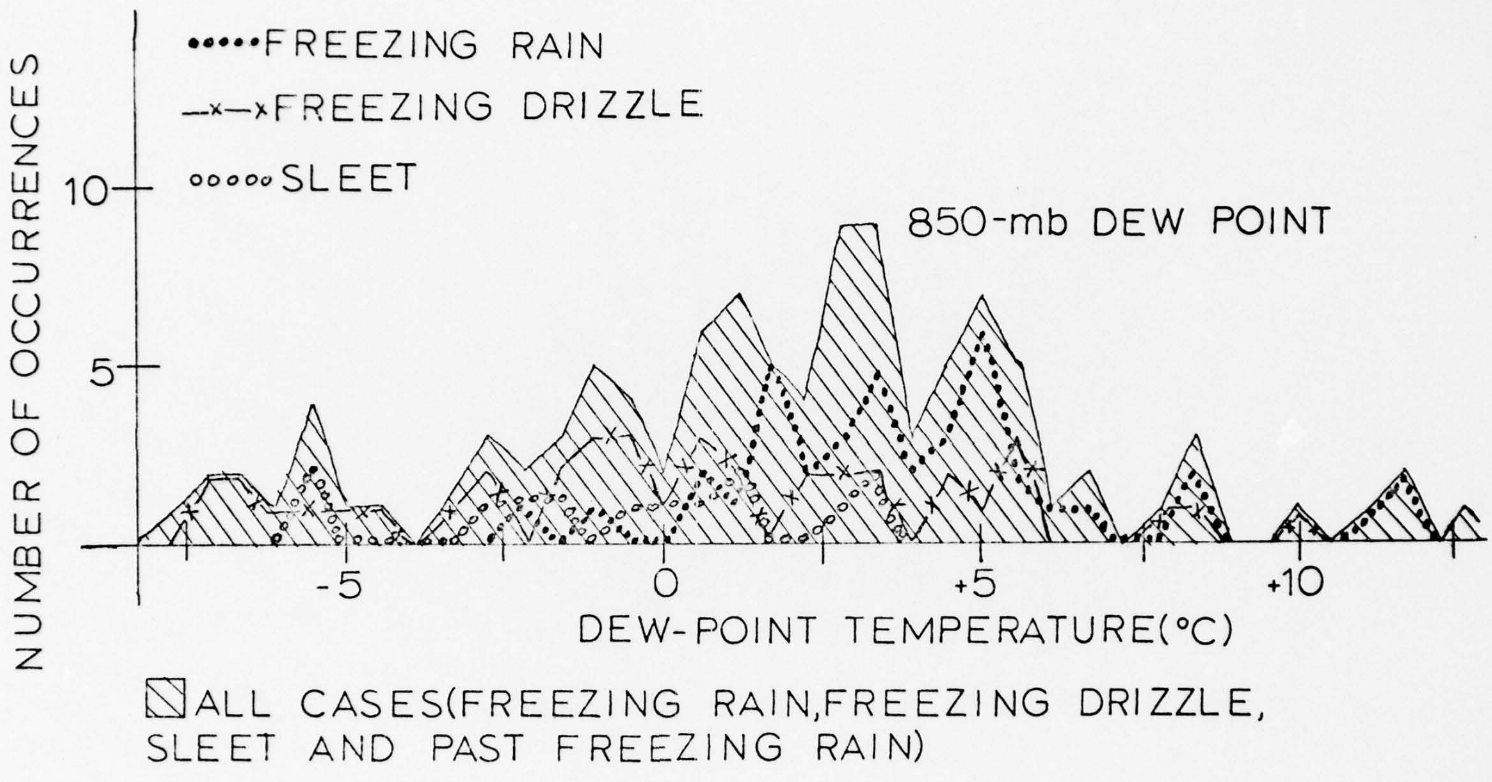

Fig. 40. The number of occurrences of freezing precipitation (various forms) over a range of 850-mb dew points (°C) for the total sample.

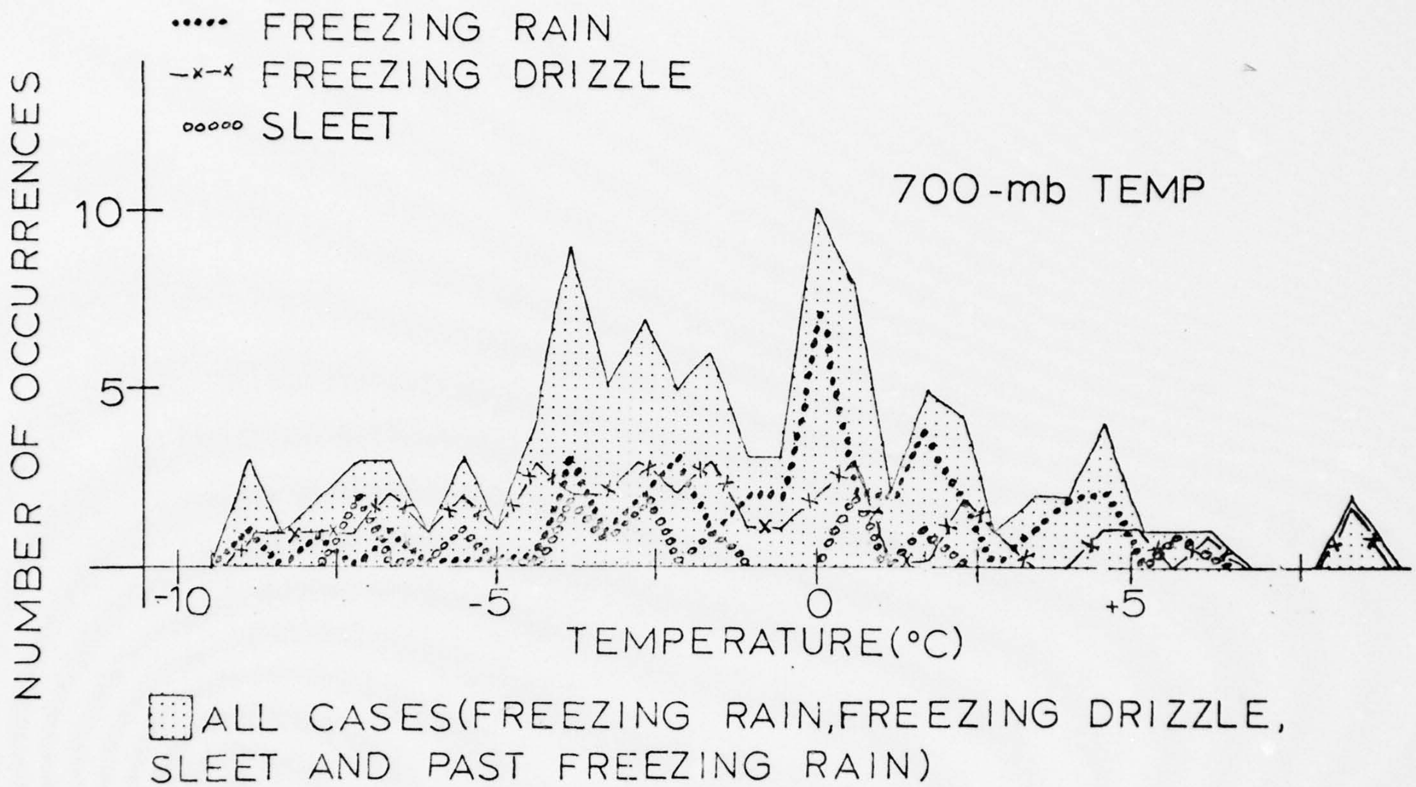

Fig. 41. The number of occurrences of freezing precipitation (various forms) over a range of 700-mb temperatures (°C) for the total sample.

3. <u>850-mb and 850-mb/700-mb averaged winds</u>

Figure 42 shows graphs of 850-mb wind direction vs number of occurrences. As was the case for the selected storms, the wind direction was predominantly southerly through westerly with a range which covers nearly the full compass.

As with the selected storms, it was found that this range could be narrowed significantly by averaging the 850-mb/700-mb wind directions. Figure 43 shows a graph of this parameter. The range is narrowed to between 125 and 315 deg for all precipitation cases and even further for cases of freezing rain alone (27 out of 32 cases between 200 and 275 deg). One sounding was removed from this study: Salt Lake City reported snow and had an averaged wind of 350 deg; it was eliminated due to its mountainous location.

Table 5 (p. 89) shows appropriate mean, mode, and median values for both parameters. One feature to note is that the mode for freezing drizzle is some 20 deg more westerly than the mode for freezing rain. This also is reflected in the differences in their mean values.

4. <u>1000-500 mb thickness</u>

Overall evaluation of this parameter (Fig. 44) showed that Tang's (1974) selection of 5460 m as a cut-off value was very good. Twenty-seven out of 29 cases of freezing rain and 49 out of 61 cases of freezing precipitation fell between 5330 m and 5440 m. The two cases of freezing rain that fell outside this range were the two mentioned previously (in chapter 4) that occurred on successive

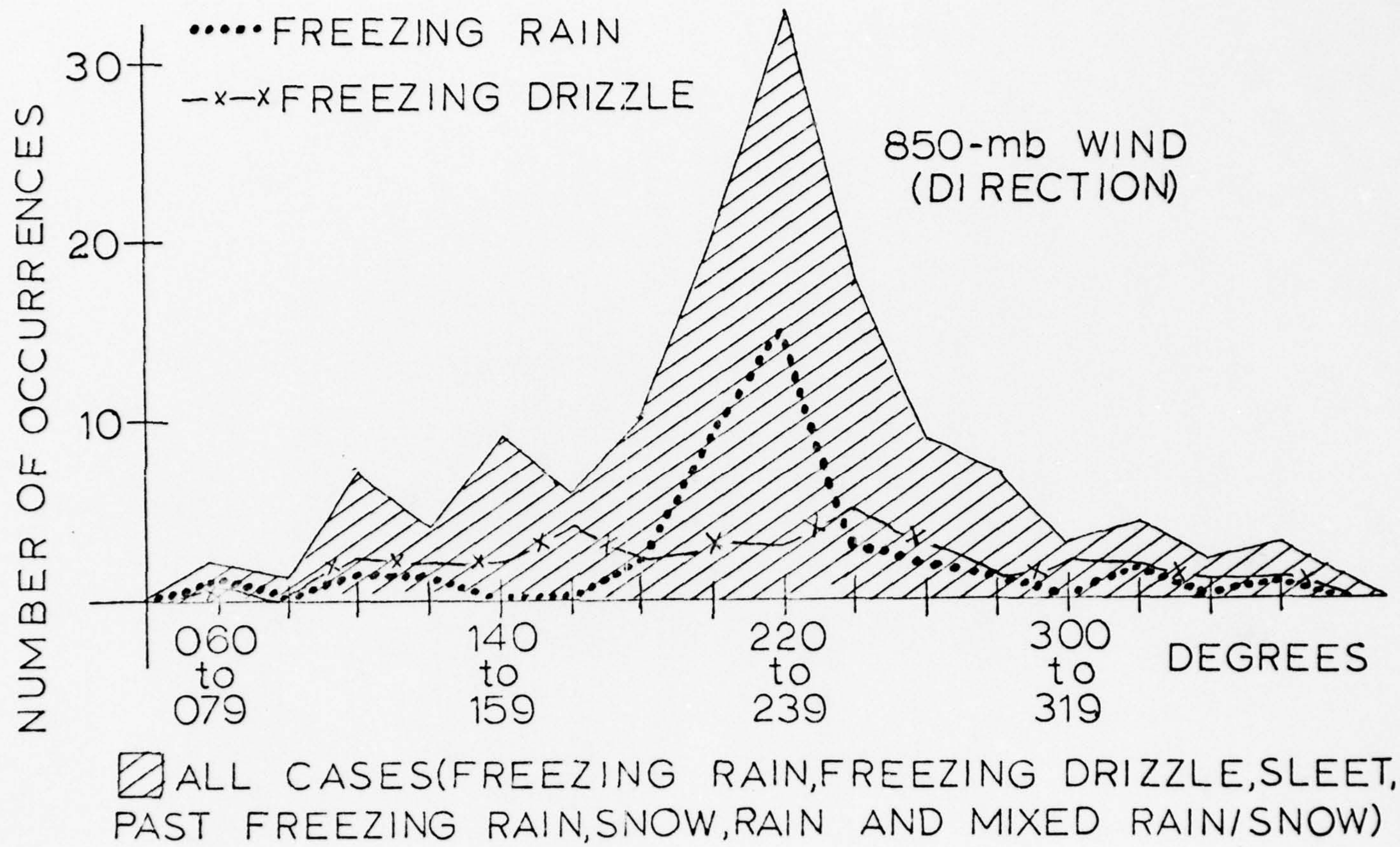

Fig. 42. The number of occurrences of precipitation (**forms of freezing precipitation** indicated separately) in 20-degree intervals of 850-mb wind direction for the total sample.

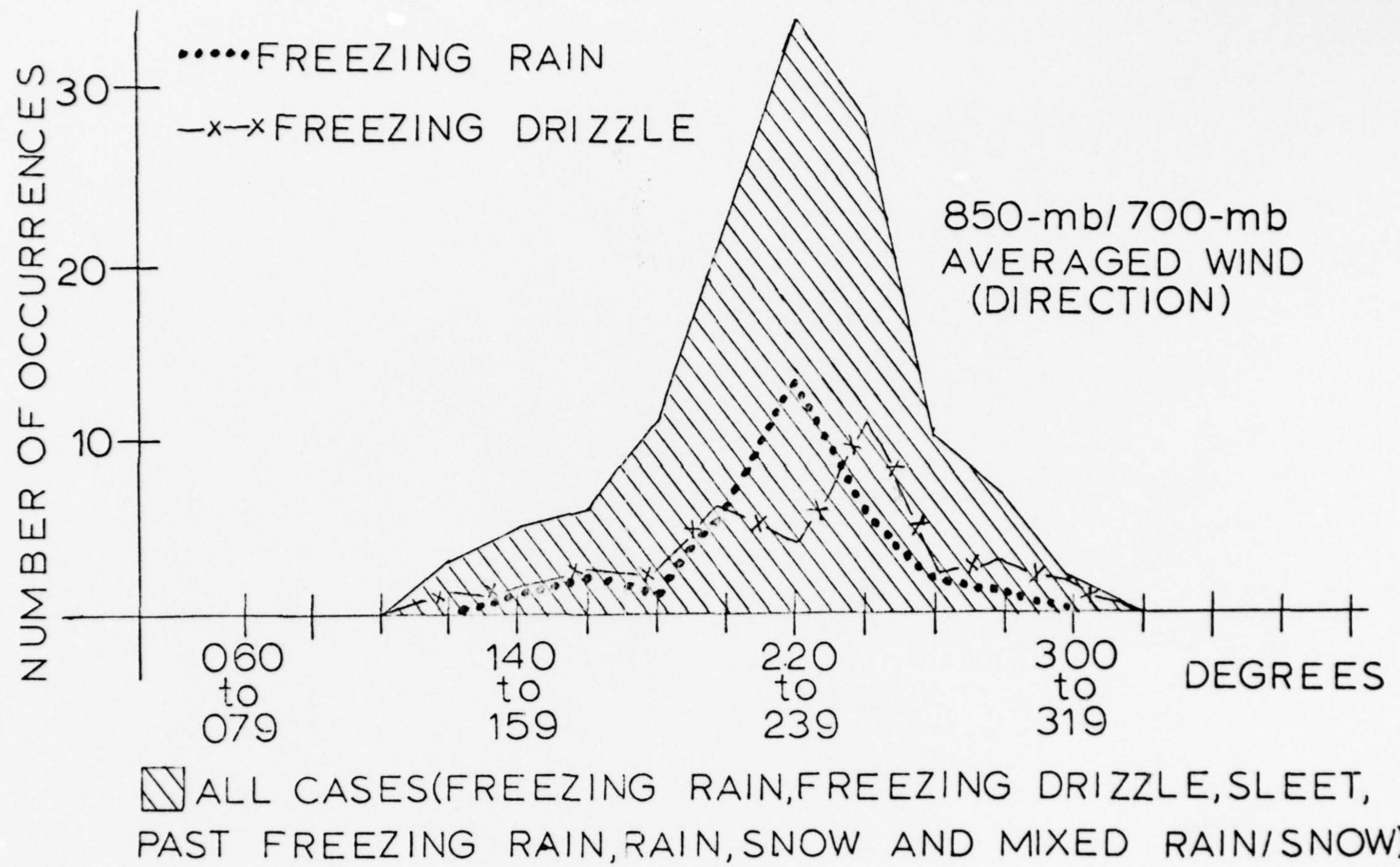

Fig. 43. The number of occurrences of precipitation (forms of freezing precipitation indicated separately) in 20-degree intervals of the averaged 850-mb and 700-mb wind directions for the total sample.

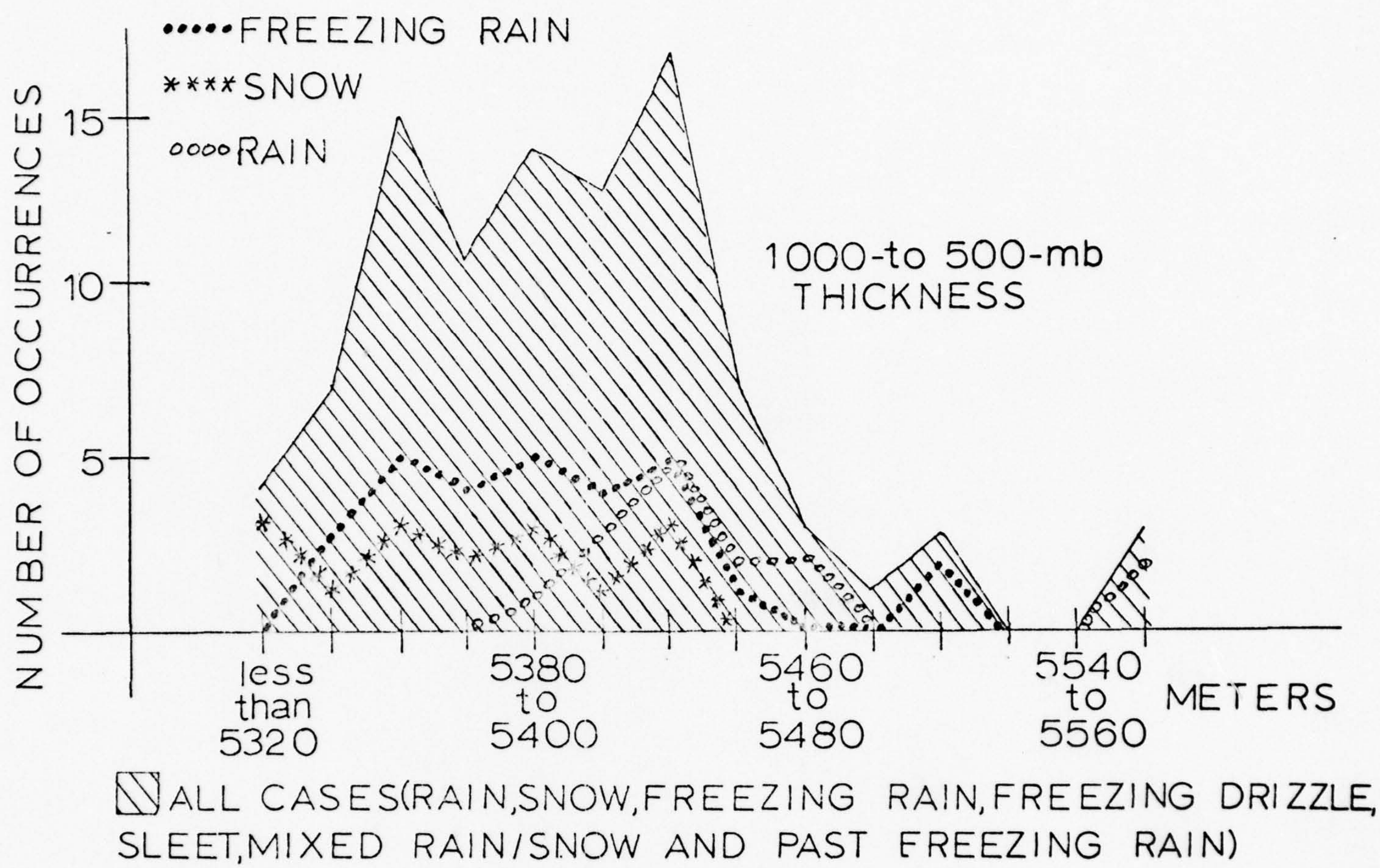

Fig. 44. The number of occurrences of precipitation (freezing rain, rain, and snow separately) in 20-meter intervals of 1000-500 mb thickness for the total sample.

soundings at Little Rock, Arkansas. Based on this sample, one would specify precipitation type by the following simple rules (with values in meters from the whole sample listed first and those from the study area in parentheses):

1. rain: values greater than 5400 (5410)
2. snow: values less than 5435 (5425)
3. mixed rain and snow: 5385-5435 (sample very small)
4. sleet: 5330-5410 (sample very small)
5. freezing drizzle: 5330-5520 (5390-5520)
6. freezing rain: 5330-5440 (5350-5440)

Also note that the mean thickness for occurrence of freezing rain dropped from a value of 5427 to 5393 when the total sample (and not just the four selected storms in the southeast) was considered. This suggests a possible stratification of the value as a predictor with lower values further north. Table 5 (p. 89) shows the mean and median values for freezing rain and freezing precipitation cases. Table 6 shows the stratification of precipitation types into various thickness ranges.

D. Combinations of parameters

1. Area of warm sector vs area of cold sector

Figure 45 shows a plot of these parameters which, as was the case for the selected storms, showed no apparent relationship between each other. A wide range in the size of the warm sector would be expected (as long as it is warm enough to melt the particles as they fall through). The wide range in the size of the cold sector was not

Table 6. Stratification of thickness values for selected storm cases and total sounding sample.

1000-500 mb Thickness Value Ranges (m)	Selected Storms (Number of Cases)							Total Sample (Number of Cases)						
	66	68	79	56	24	61	71	66	68	79	56	24	61	71
less than 5320	0	0	0	0	0	0	0	0	0	0	0	1	0	3
5320-5340	0	0	0	0	0	0	1	3	0	1	2	0	0	1
5341-5360	1	0	0	0	1	0	0	5	0	0	3	4	0	3
5361-5380	1	0	0	0	0	0	1	4	0	2	2	1	0	2
5381-5400	1	0	1	0	0	0	3	5	1	2	1	1	1	3
5401-5410	1	0	0	1	0	0	0	3	0	1	3	0	2	1
5411-5420	0	0	0	1	0	1	0	1	0	0	1	0	1	0
5421-5430	1	0	0	0	0	3	1	3	1	0	1	0	3	2
5431-5440	1	0	0	0	0	1	0	2	0	0	2	0	2	1
5441-5450	0	0	0	0	0	0	0	1	0	0	0	0	0	0
5451-5460	0	0	0	1	1	0	0	0	0	1	2	1	2	0
5461-5470	0	0	0	1	0	0	0	0	0	0	1	0	1	0
5471-5480	0	0	0	0	0	1	0	0	0	0	0	0	1	0
5481-5490	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5491-5500	0	0	0	0	0	0	0	0	0	0	1	0	0	0
5501-5520	2	0	0	1	0	0	0	2	0	0	1	0	0	0
5521-5540	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5541-5560	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Over 5560	0	0	0	0	0	1	0	0	0	0	1	0	2	0

where: 66 = freezing rain; 68 = mixed rain/snow; 79 = sleet; 56 = freezing drizzle; 24 = past freezing rain; 61 = rain and 71 = snow.

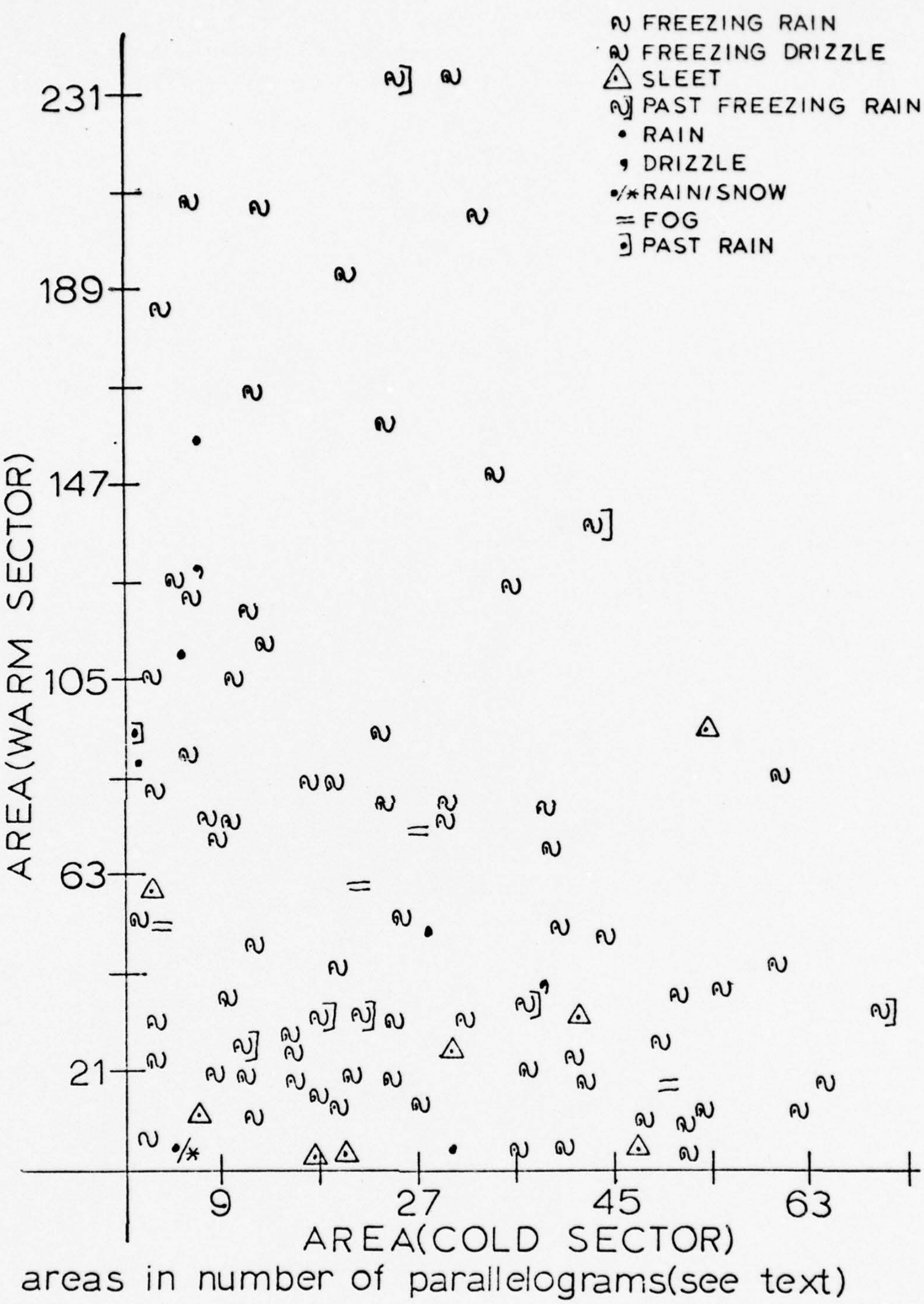

Fig. 45. Area of warm sector vs area of cold sector (within lowest 700-mb) for soundings from total sample.

expected, as it was felt that a smaller upper limit would result since beyond a certain point the lower portion of the sounding must become too cold and sleet or snow result. If any cut-off could be derived from this study, it would have to be around 60 or 65 parallelograms. Note, however, that most occurrences are between values of 5 and 45 (for the cold sector).

2. Top of cold air vs top of warm air (0°C crossings)

Figure 46 shows a plot of these two parameters for the total sampling. No obvious relationship was apparent between the two, but as was the case for the selected storms in chapter 4, some ranges of values could be derived. The first crossing of the 0°C (top of the cold air) line usually fell between 300 and 1200 m above the surface, while the second crossing (top of the warm air) occurred over a wide range of values from 1500 m upward.

3. Absolute coldest vs absolute warmest temperature below 700 mb

Results found by plotting these two values for all cases are shown in Fig. 47. A fairly distinct grouping of the freezing precipitation cases can be seen as well as areas of snow, rain, and sleet. However, since these parameters are not forecast as easily, no forecast tool was derived from these results.

4. 850-mb temperature vs surface temperature

These parameters combine the desired easy availability with fairly well-defined relationships for each of the precipitation

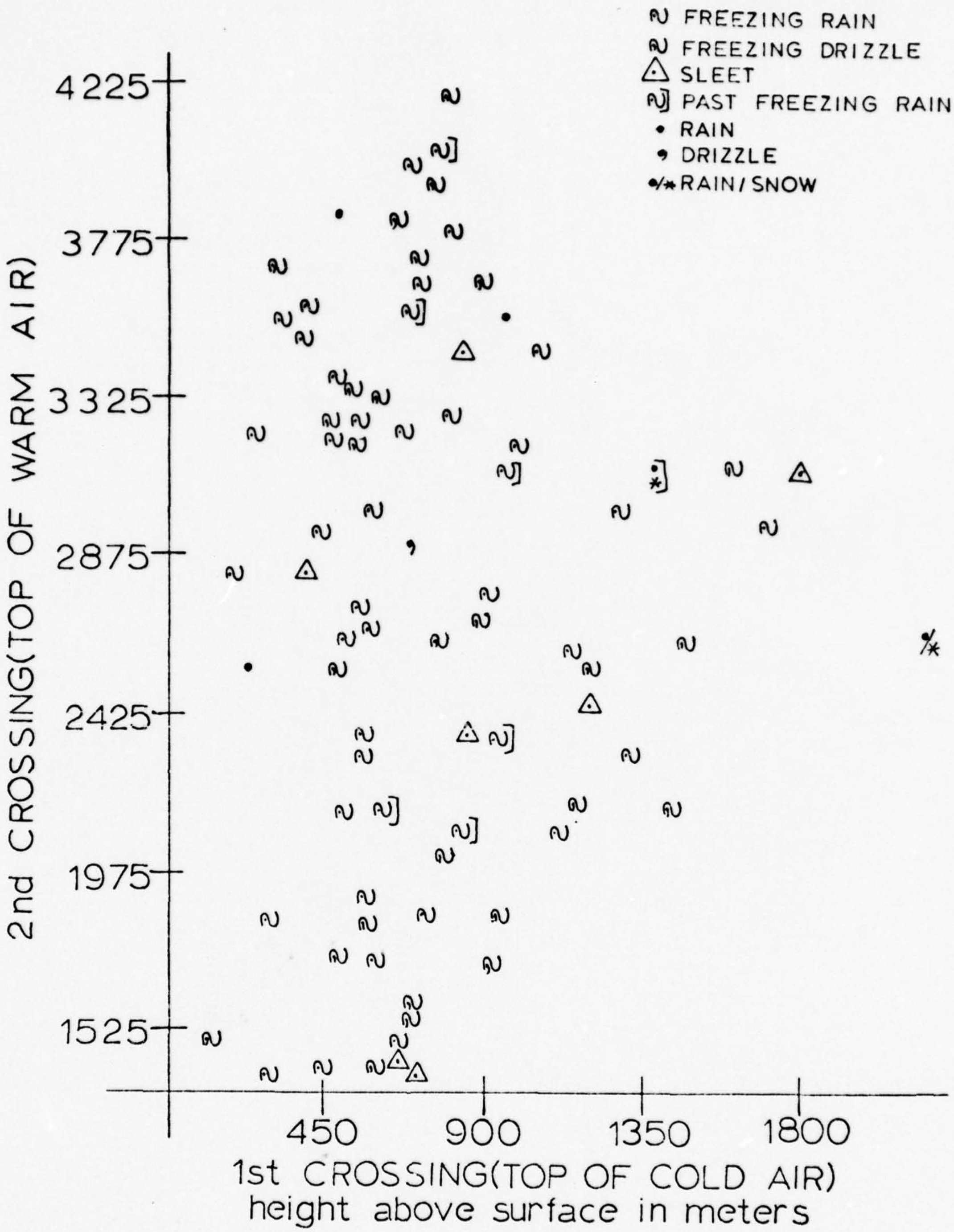

Fig. 46. Top of cold air sector (first crossing of 0°C isotherm) vs top of warm sector (second crossing of 0°C isotherm) for soundings from total sample.

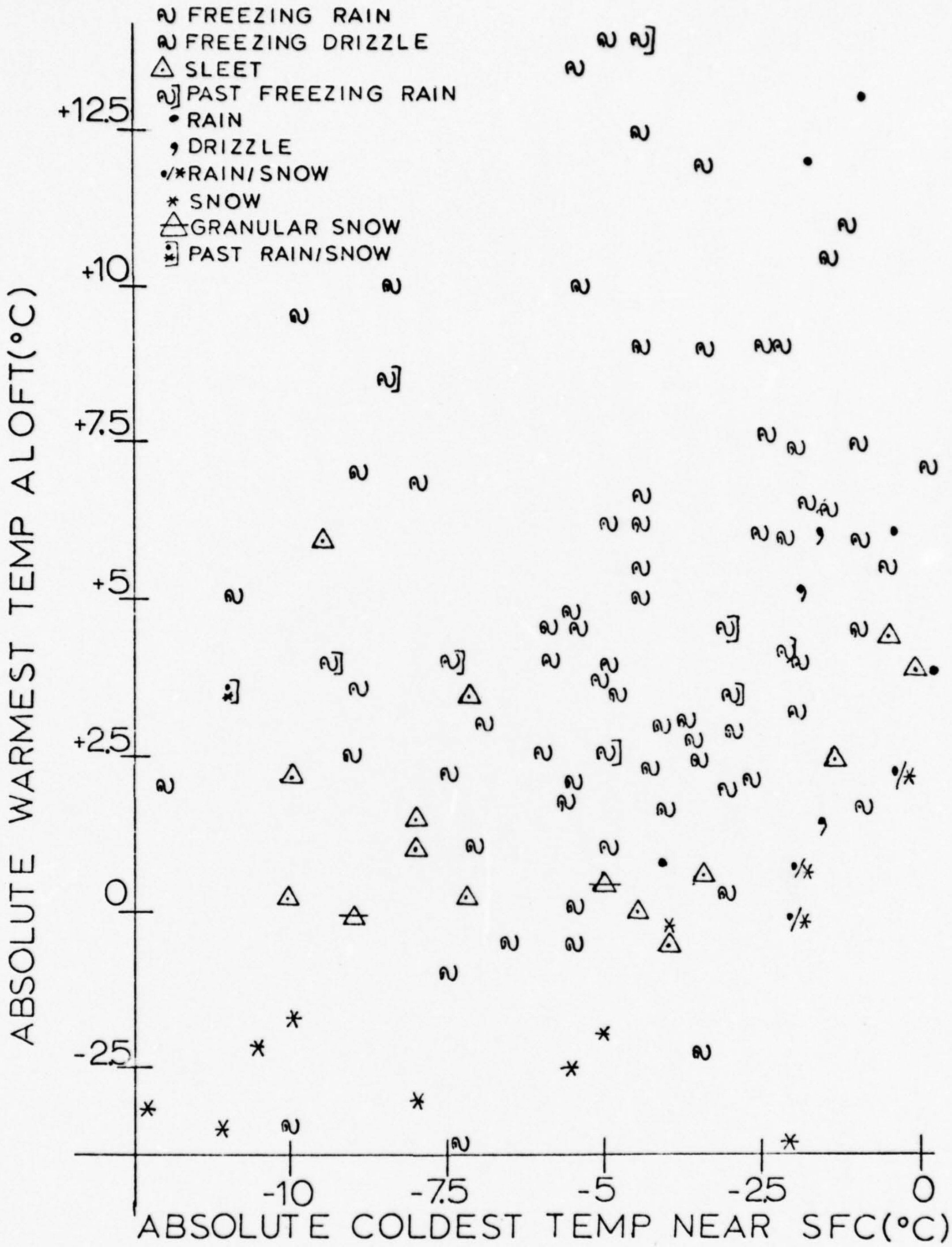

Fig. 47. Absolute coldest vs absolute warmest temperatures (°C) in lowest 700-mb for soundings from total sample.

forms, thus making them ideal forecast parameters. Figure 48 shows a plot of these two parameters in symbols indicating resulting weather form for the entire sample. These results when coupled with the results from other surface and upper-air parameters formed the backbone for the final decision checklist and decision graph in this study. Due to a profusion of occurrences near the center of the figure, not all the cases could be plotted there. Those that were plotted are representative of the total sample.

E. Other parameters and features to consider

1. Drop size

Much could be written in regard to this parameter and its effect on resultant precipitation form. Discussions of this can be found in the work of Weickmann (1957), Petterssen (1969), and Neiburger, Edinger, and Bonner (1973). Figure 49 shows a plot of fall velocities of various particles (Weickmann, 1957). The main thing to remember is that the size of the drop affects the time required to freeze it (both because of its physical size and because larger drops fall faster) and thus drop size could prove to be a "critical factor" (Neiburger, Edinger, and Bonner, 1973). Regardless, drop size will not be considered further in this study because of the inability of the forecaster to predict this parameter.

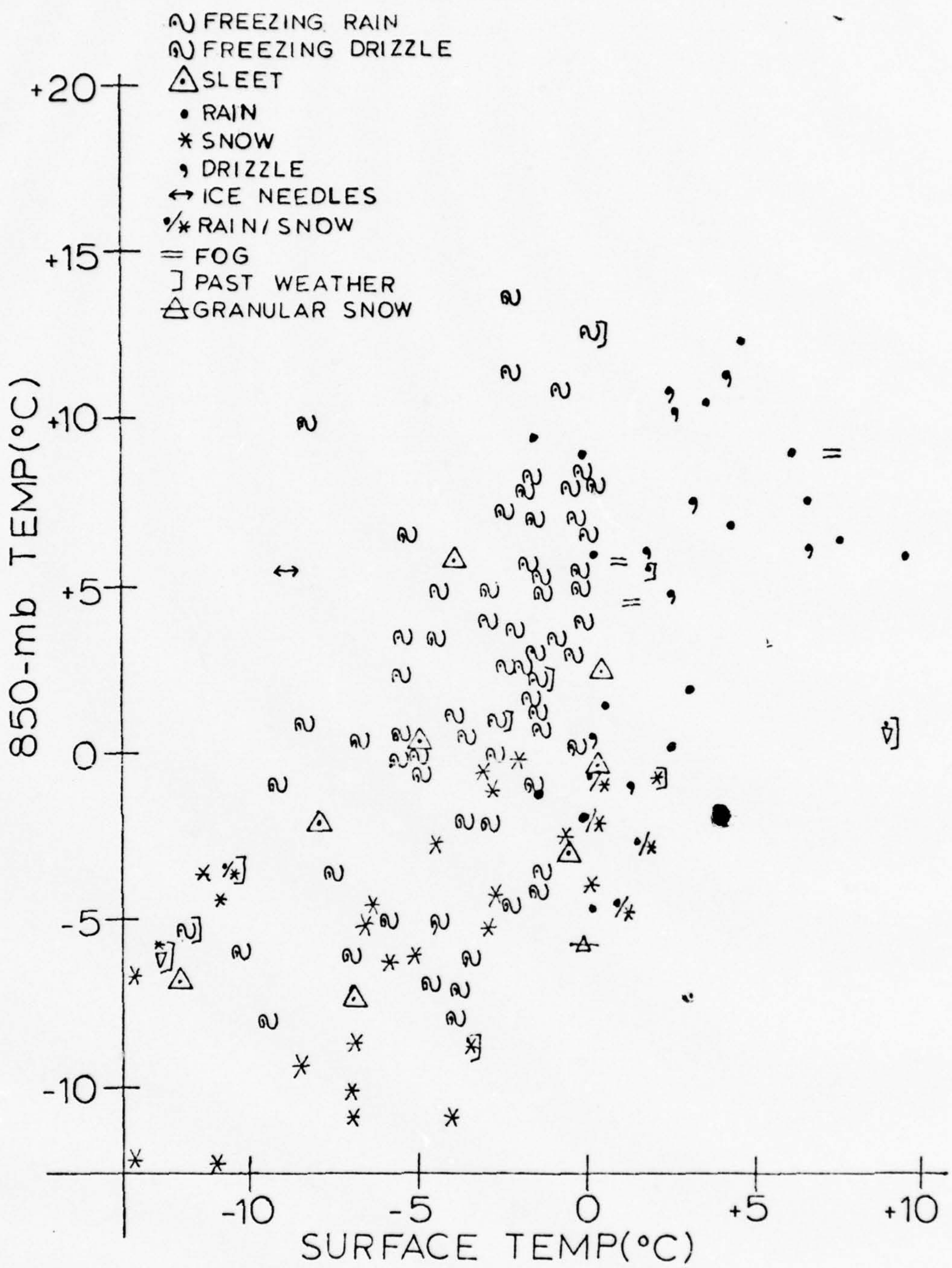

Fig. 48. Surface temperature vs 850-mb temperature (°C) for soundings from total sample.

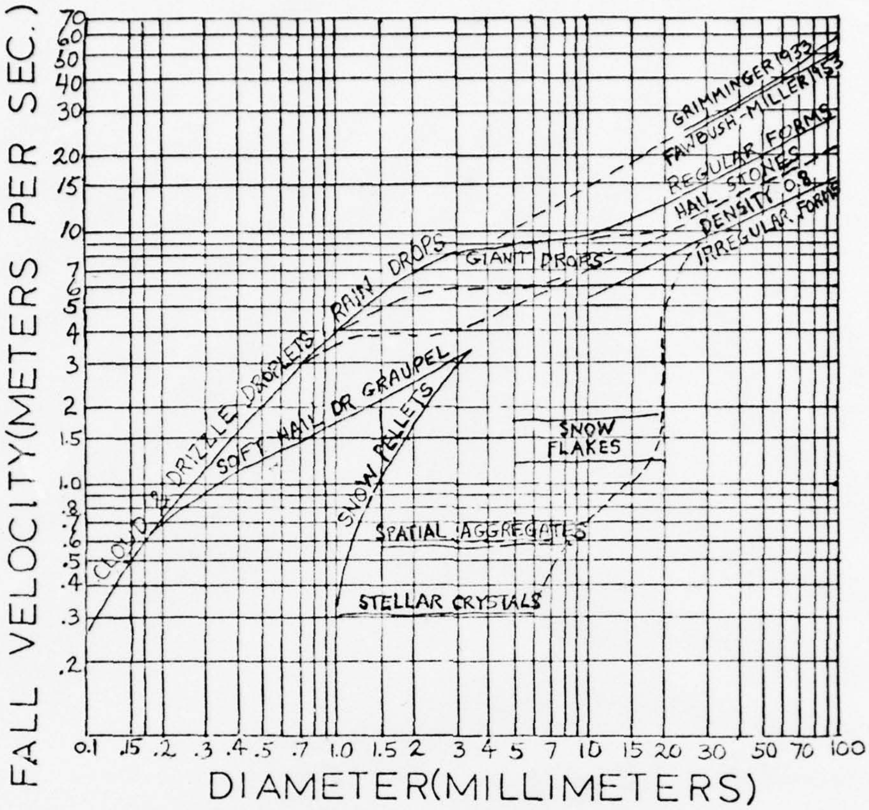

Fig. 49. Fall velocities for various drop sizes (after Weickmann, 1957).

2. Topography

This parameter was discussed in chapter 1, and as was noted there, it can play a substantial role during an ice storm. In an area of hilly terrain, an ice storm can be severe at higher elevations and yet leave the lower elevations unaffected. The important element here is for the forecaster to take into account both his own elevation and that of the surrounding area. A storm which produced no freezing precipitation previously can upon encountering a slight rise in elevation become a full-fledged ice storm.

3. Coldness of surface prior to storm

This parameter also can have a large effect on an area, for if the ground is already below freezing, then falling rain could freeze on contact thereby producing freezing precipitation (even though the air temperature at the surface may remain slightly above freezing). This occurs most often in the more northerly states, where prolonged periods of below freezing temperatures are most common, but does on occasion happen in the Southeast. The effect is to eliminate the need of much (if any) of a cold sector near the surface, thus leaving only the requirement for the warm, moist, overrunning air.

4. Flattening of cold air dome as it moves southward

One more phenomenon which at least should be noted when attempting to forecast an approaching potential ice storm is the flattening of the cold air dome as it pushes southward. This occurrence was noted by Harms (1974) in his discussion of the February 1973 snowstorm.

The effect is to reduce (in depth) and spread out the cold air as it moves south. Thus one should choose with care any station to the north as a representative sounding (reflecting the approaching air mass). This flattening of the cold air then should be taken into account when any compilation of amount of cold air near the surface is made with the result important (perhaps even critical) in forecasting ice storm occurrence.

VI. FORECASTING TECHNIQUES AND VERIFICATION

A. General discussion

Although more soundings resulted from outside the study area (about 65% of the total), they only enhanced the findings based initially on the more limited sample derived from the study area alone. In fact, the decision checklist and decision graph which resulted from this study verify best for the Southeast although holding up well for all areas (particularly those east of the Rocky Mountains).

B. Checklist and decision graph

Always the first concern of this study was to try to reach conclusions based on parameters readily available to the forecaster so that an accurate decision could be reached as quickly as possible. After examination of all the parameters previously mentioned, the ones which best combined the qualities of easy access with fairly distinctive limits were selected. A decision checklist comprised of these parameters (surface temperature, surface dew point, 850-mb temperature, 1000-500 mb thickness, and the averaged 850-mb/700-mb wind direction) was then constructed. All of these parameters had been included in previous studies except for the averaged 850-mb/700-mb wind direction. The important difference here was that this study attempts to combine more parameters than any previous study and to incorporate more detailed limits. Also added to the checklist is a temperature/dew point spread as an indicator of moisture.

This checklist is reproduced as Table 7.

If the forecast value of each parameter falls within the extreme values on the decision checklist, the forecaster proceeds to the decision graph (Fig. 50) to obtain the most likely forecast of precipitation type.

C. AVE data verification

The AVE data (as described in chapter 2) was used for verification. This verification was accomplished by looking at each sounding individually, checking with the accompanying synoptic chart to determine weather type, then using the decision checklist and decision graph, to obtain a "forecast" weather type. When the two weather types were the same, a hit was scored and when they differed a miss was scored. One problem was the subjectiveness of the AVE synoptic maps in regard to weather types. For this reason, only cases within well-defined weather areas were chosen and evaluated.

Seventy out of 75 cases observed verified as hits for a 93.3% rate. Of this, however, only 6 cases of freezing precipitation were observed with 5 hits and 1 miss (83.3% for small sample) with the large majority of the precipitation cases being snow, which verified extremely well. Also, the cases of freezing precipitation occurred north of the area of study (West Virginia, Ohio, Kentucky) and thus the need for a more representative verification sample arose.

Table 7. Decision checklist for freezing precipitation (values derived from study sample).

	Parameter	Ideal range	Extreme range
1.	Surface temperature	0 to -4°C	+1 to -11°C
2.	Surface dew point	0 to -5°C	0 to -13°C
3.	850-mb temperature	+1 to +6°C	-8 to +15°C
4.	1000-500 mb thickness	5330 to 5440 m	5320 to 5510 m
5.	Temp/dew point spread	850-mb: 1°C or less SFC: 3°C or less	6°C or less 7°C or less (but one of them 3°C or less)
6.	850-mb/700-mb averaged wind direction	200 to 260 degrees	135 to 310 degrees

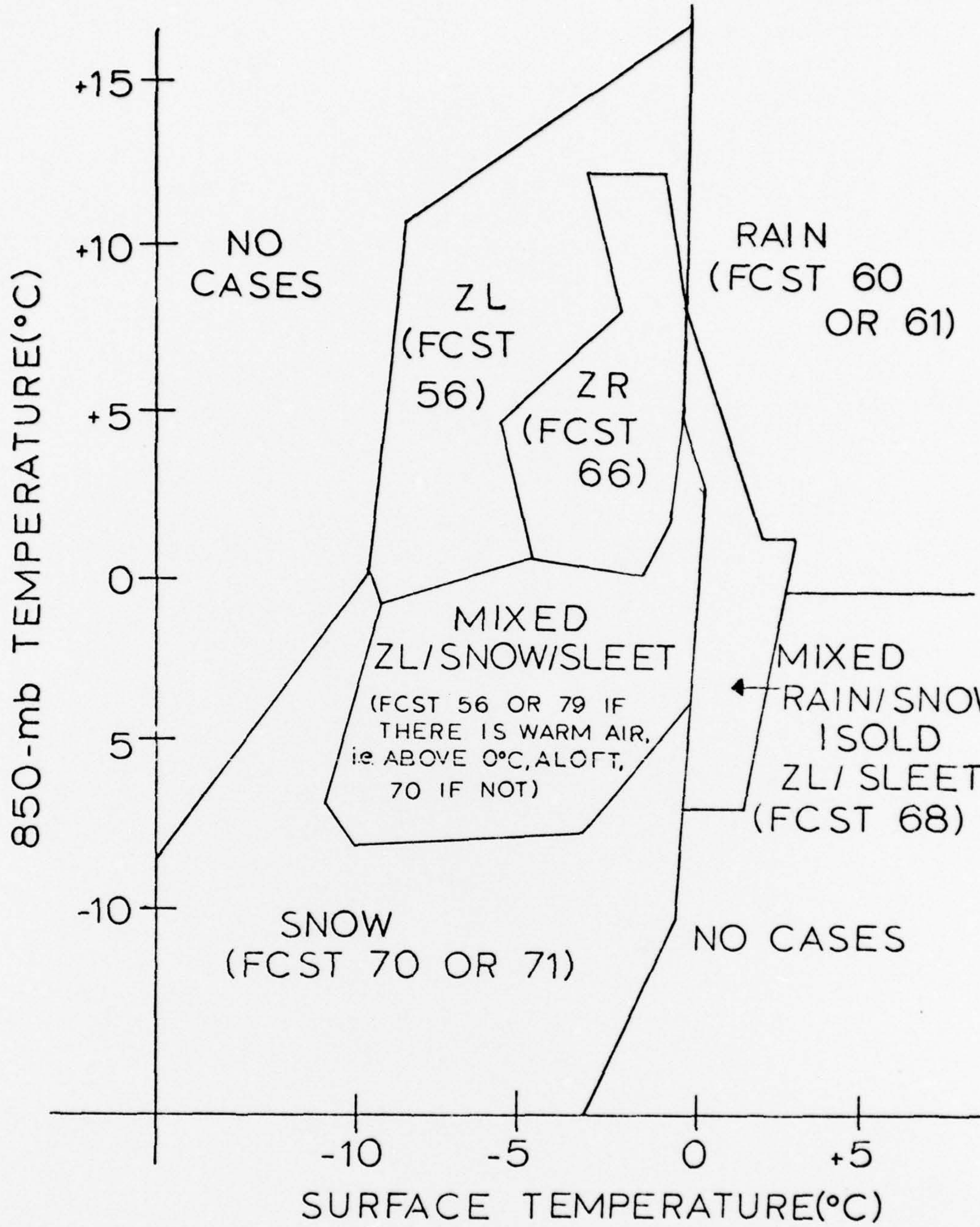

Fig. 50. Cumulative decision graph with most probable forecasts indicated. Synoptic code designators are used (56 = freezing drizzle [ZL], 66 = freezing rain [ZR], 68 = mixed rain and snow, 79 = sleet, 60 [or 61] = rain, and 70 [or 71] = snow).

VII. CONCLUSIONS AND RECOMMENDATIONS

Although it is felt that with the decision checklist and decision graph produced by this study, the forecaster should greatly improve his chances of forecasting freezing rain (particularly as opposed to freezing drizzle or sleet), it is by no means a finished product. As with any forecast tool, it is only as good as the predicted values for the parameters. One recommendation is that a full year of data be put through the checklist and graph to test how accurate it really is and in particular to test how often it forecasts freezing precipitation and no such occurrence follows. This could be done most expediently by use of a computer program and a disc of data.

A second recommendation would be to add vectorially the 850-mb/700-mb winds and then take the average. Combining the two in this manner would take into account the wind magnitude at each level instead of strictly the wind direction. It is believed that in this fashion the 850-mb/700-mb wind parameter used in the decision checklist could be narrowed even further in regard to its limits and thus could become an even more effective forecast parameter.

Another study which could enhance the results is to parameterize the temperature of the ground prior to the occurrence of freezing precipitation. A cold sector needs to be much less strong if the ground has been cold for a relatively long period prior to the occurrence of a storm to result in freezing precipitation (see discussion in chapter v). Conversely, if the ground is very warm, the opposite is true.

Finally, the decision checklist and graph can be enhanced only by plotting more reports of freezing precipitation and adding them to the sample. It is believed that with suitable modification to the values in the checklist, the checklist and graph could be adopted for use in other areas of the world. This, however, would require careful prior research.

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APPENDIX

IDENTIFICATION OF STATIONS

Identifier	Location
ABI	Abilene, Texas
ABQ	Albequerque, New Mexico
AHN	Athens, Georgia
ALB	Albany, New York
AMA	Amarillo, Texas
AYS	Waycross, Georgia
BNA	Nashville, Tennessee
BOI	Boise, Idaho
BRO	Brownsville, Texas
BUF	Buffalo, New York
BVE	Boothville, Louisiana
CHS	Charleston, South Carolina
DAY	Dayton, Ohio
DCA	Washington, D.C.
DDC	Dodge City, Kansas
DRT	Del Rio, Texas
FNT	Flint, Michigan
FTW	Fort Worth, Texas
GGG	Longview, Texas
GJT	Grand Junction, Colorado
GRB	Green Bay, Wisconsin
GSO	Greensboro, North Carolina
GSW	Dallas/Fort Worth, Texas
HAT	Cape Hatteras, North Carolina
HTS	Huntington, West Virginia
IAD	Washington, D.C.
JAN	Jackson, Mississippi
LCH	Lake Charles, Louisiana
LIT	Little Rock, Arkansas
MAF	Midland, Texas
MGM	Montgomery, Alabama
OKC	Oklahoma City, Oklahoma
OMA	Omaha, Nebraska
PHL	Philadelphia, Pennsylvania
PIA	Peoria, Illinois
PIT	Pittsburgh, Pennsylvania
RAP	Rapid City, South Dakota
SHV	Shreveport, Louisiana
SLC	Salt Lake City, Utah
SLO	Salem, Illinois
TIK	Tinker AFB, Oklahoma City, Oklahoma
TOP	Topeka, Kansas
TPA	Tampa, Florida
UIC	Quillayute State, Washington

APPENDIX (Continued)

Identifier	Location
UMN	Monett, Missouri
VCT	Victoria, Texas

VITA

William R. Young was born on December 27, 1947, in Foxboro, Massachusetts, as the first of three children to Robert B. and Margaret L. Young. He attended first through seventh grades at schools in Mansfield, Massachusetts, and eighth through twelvth in Garden Grove, California (after his family moved there in 1960) and graduated in 1965 from Santiago High School.

He received his Bachelor of Science degree in Social Science and Commission as a 2nd Lieutenant in the U.S. Air Force from Colorado State University in December 1969. Further schooling included Air Force Basic Meteorology at Texas A&M University and radar and satellite interpretation courses at Chanute AFB, Illinois. Military assignments included two years at Dobbins AFB, Georgia, and three and a half years at Air Force Global Weather Central, Offut AFB, Nebraska.

Sponsored by the Air Force Institute of Technology, U.S. Air Force, he entered Texas A&M University in June 1976 to pursue the degree of Master of Science in Meteorology.

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